Megaregional Transportation System Resilience Planning

Principal Investigator: Lisa Loftus-Otway

Graduate & Undergraduate Research Assistants:

Paulina Urbanowicz-Pollock and Roxanne Lin

November 2019

A publication of the USDOT Tier 1 Center:
Cooperative Mobility for Competitive Megaregions
At The University of Texas at Austin

Technical Report Documentation Page

1. Report No. CM2-32	2. Government Accession No.	3. Recipient's Catalog No. ORCID: 0000-0001-5143-9513
4. Title and Subtitle Megaregional Transportation System Resilience Planning		5. Report Date: November 2019 6. Performing Organization Code
7. Author(s) Paulina Urbanowicz-Pollock; Lisa Loftus-Otway; Roxanne Lin		8. Performing Organization Report No. CM2-# 32
9. Performing Organization Name and Address The University of Texas at Austin School of Architecture 310 Inner Campus Drive, B7500 Austin, TX 78712		10. Work Unit No. (TRAIS) 11. Contract or Grant No. USDOT 69A3551747135
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Transit Administration Office of the Assistant Secretary for Research and Technology, UTC Program 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Technical Report conducted September 2018 - June 2019 14. Sponsoring Agency Code
15. Supplementary Notes Project performed under a grant from the U.S. Department of Transportation's University Transportation Center's Program.		

16. Abstract

The contents of this report contribute to the foundational research for megaregional transportation resilience planning. Megaregions contain the majority of America's population and economic centers, and experience various levels of devastating impacts as a result of gradual climate change impacts and natural disaster threats. This work defines transportation resilience and outlines existing funding sources available for resilience planning and projects. It also includes a spatial resilience case study that evaluates three megaregions bordering the Gulf of Mexico, a series of three-pager resilience profiles that outline major disaster threats to each U.S. megaregion, and examples of transportation resilience planning efforts to date. With federal financial assistance, state and regional transportation agencies have spearheaded the effort to collaborate on formal and informal forms of resilience planning at the regional and megaregional scale.

17. Key Words Megaregion, resilience, natural disaster, hurricanes, extreme weather, MPOs, USDOT	18. Distribution Statement No restrictions.		
19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 120	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

List of Figures

List of Tables

Executive Summary

Between 2000 and 2019, the United States experienced 170 disaster events that exceeded a billion dollars in total impact.[1] As natural disaster events increase in frequency and intensity around the world as a consequence of climate change, communities will need to contend with the challenge of preparing for potential future disaster events, and learning how to set policies, funding, and procedures in place to swiftly re-establish normalcy after an event. Economic and population centers that form identified U.S. megaregions should develop strategies to become more resilient in the face of what is expected to be increasing events of severe magnitude and one-in-a-hundred-year type disaster events. Effective and safe transport networks are critical to pre- and post-disaster operations. Transportation networks serve as the key facilitator to connect people to temporary shelter and resources, and for goods, services, and emergency providers to deliver food, medicines, and other resources post-disaster. Transportation networks are also a primary factor in megaregional theory, because transport systems connect concentrated populations and economies throughout a megaregion and to rural and urban areas that are not contained within a megaregion but supply a megaregion. This report seeks to apply a megaregional lens to the question of resilience to natural disasters and longer-term climate change impacts and contemplates the future role of regional transportation agencies in developing and implementing resiliency policy.

Applying megaregional theory to disaster resilience is a nascent concept. Estimating economic impact of natural disasters on transportation systems is not easily accomplished. Economic impact methodologies utilized in current estimations at local, regional, and state scales use a wide range of methodologies, estimates, and data. However, data and methodologies specific to megaregions do not yet exist. While megaregions encompass many regional centers, they also frequently encompass small population centers in between, where data may be most available at the county level. The discrepancy in agency level of data collection—combined with the fact that damage estimates for transportation infrastructure are often coupled with damage estimates for other infrastructure—makes it difficult to isolate a figure for economic impact resulting from damage to transport infrastructure. This discovery led us to take a step back during the project and decide to contribute to the foundation of megaregion resiliency by creating resources for future researchers to easily access and use to build off. This report provides insight to transport agencies

[1] (National Centers for Environmental Information, 2019)

in terms of the role that different federal agencies have in this conversation, and examples of transport resilience projects at the state and regional scale. It also evaluates the roles that regional transportation agencies might play in moving the needle forward on transport system resilience. It includes a spatial analysis of post-disaster resilience of three megaregions in terms of population and employment, and three-page reference resilience profiles that illustrate specific natural disaster and climate threats to each of the 11 U.S. megaregions.

The results of this work indicate that state and regional transportation agencies across the country are spearheading efforts of megaregional transportation resilience through multi-agency collaborations. Working toward a shared concern such as gradual effects of climate change or natural disaster threats, agencies have organically formed collaborative arrangements to apply for federal funding and work toward an improved and more resilient transport system. Our findings also illuminate that regional transportation agencies can elevate the investment in transportation system resilience within their existing federal mandate by prioritizing funding for projects that will lead to transport system resilience. Counties and state governments must regularly complement the investment in regional transportation to ensure megaregion resilience. We also found that metropolitan planning organizations (MPOs) within a megaregion have a vested interest in the resilience of other metropolitan areas within a given megaregion. When one regional employment or population center is impacted by a natural disaster event, supply chains and typical flows of goods and business processes are disrupted. Disruptions resulting from closed airports, seaports, flooded railroads, or flooded roads directly impact how and when goods are delivered to their end destination. This can lead to larger-scale economic disruptions and ramifications.

It is our hope that this report contributes to the development of methodology to estimate the megaregional impacts of damage to transport assets from natural disaster events, and that it provides further motivation for future research that moves efforts of resilient megaregional transport systems forward.

Chapter 1. Introduction

In 2007, researchers with the Regional Plan Association (RPA) published a report identifying a new geographic scale for infrastructure planning and investment: 11 emerging megaregions across the United States. The theory of megaregions is based upon the observation that regions united by transport, geography, and cultural and human connections are most economically competitive when considered holistically, because interdependencies exist beyond the metropolitan scale.[2] Geographic boundaries were drawn around areas that were naturally converging and connected population centers, as displayed in **Figure 1**. The Federal Highway Administration (FHWA) defines a megaregion as "a network of urban clusters and their surrounding areas, connected by the existing economic, social, and infrastructure relationships."[3] Building on the foundation of megaregional theories, FHWA identified the need to evaluate planning challenges beyond existing jurisdictional lines (state and regional), which traditional planning practices are often bound within.

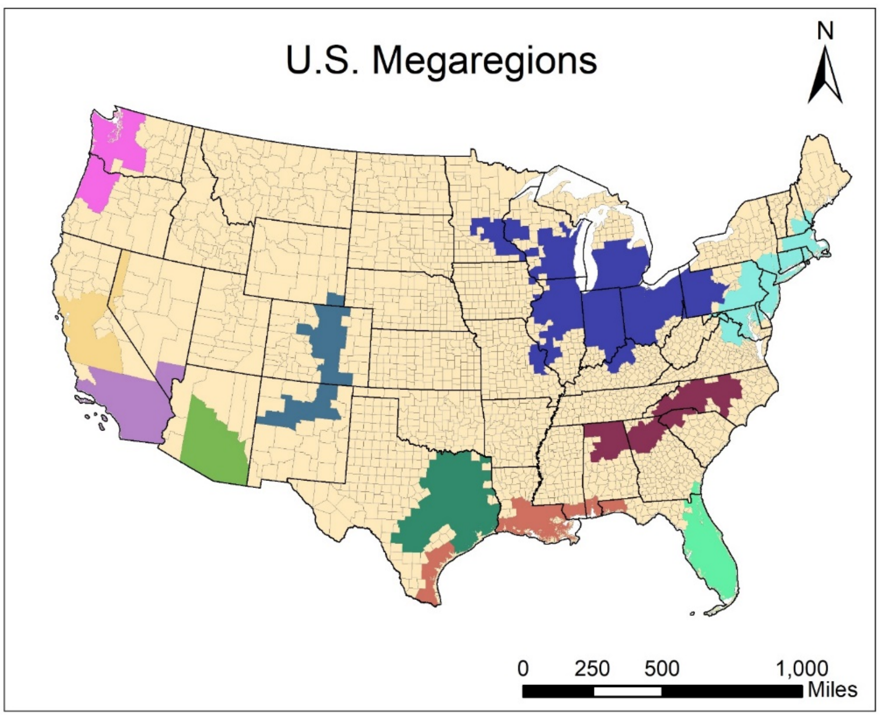

Figure 1: Megaregions in the United States, designated by the Regional Plan Association.

[2] (Regional Plan Association, n.d.)
[3] (FHWA, n.d.-e)

In 2009, FHWA identified 13 megaregions varying slightly from the megaregions identified by America 2050. The identification of FHWA-recognized megaregions led to the development of research centers like CM^2, which have expanded the breadth and depth of issues evaluated with a megaregional lens and helped to make progress on various planning and policy issues that occur outside of existing jurisdictional borders.

Transportation is commonly cited as one of the networks that links regions together within a megaregion. Disruptions to a transportation system resulting from a natural disaster can have wide-ranging impacts on the well-being of residents of a region, and subsequent impacts to economic drivers of a regional, megaregional or national economy.[4] Rodrigue et al. identify multiple key drivers that impact the level of risk and threats to disruptions in the transportation system, including infrastructure and economic interdependencies, increased mobility, centralization and concentration of distribution, and urbanization.[5] Many of these drivers parallel as key drivers for megaregional planning and infrastructure development. Because megaregions are interconnected economic and population centers, they are a collection of high concentrations of people, and create an environment with high concentrations of risk.[6] The concentration of economic activities, also an underpinning component of the evolution of megaregional planning theory, leads to potential for major disruptions to the flow of goods and economic activities.

Increasing interdependencies of economies and transport systems suggest that interconnected regions have a vested interest in the success and resilience of other regions within a megaregion. Disruptions to the transport system can impact supply chains to varying degrees based on disaster scale and extent of damage, and may subsequently cause regional, national, or international economies to suffer until a region can return to its level of functioning prior to the event. Therefore, the economic competitiveness of a megaregion necessarily depends on its resilience to foreseen and unforeseen disasters. For example, the impact of Hurricanes Katrina and Rita during the 2005 hurricane season crippled infrastructure across southern and southeastern states.[7] Ports, railroads, key bridges, and more were damaged and out of commission for weeks, and in some cases took

[4] (Rodrigue, Comtois, & Slack, 2017)
[5] (Rodrigue, Comtois, & Slack, 2017)
[6] (Rodrigue, Comtois, & Slack, 2017)
[7] (Grenzeback, n.d.)

months or years to return to pre-disaster conditions. As a critical piece of the nation's oil/gas/energy network, ripples were felt across the U.S. Over 27% of national domestic oil production was stalled in the aftermath of Katrina and Rita, which represented almost 90% of oil production in the Gulf of Mexico. During this time, about 42 million gallons of gasoline per day was not produced, leading to nationwide impacts of rising prices for gasoline.[8] Subsequent operations and ability for economies to rebuild to prior operating levels can have a delayed and continued negative economic impact on the nation. The long-term nature of planning and implementing transportation infrastructure projects can require decades of rebuilding to resume levels of operations prior to a natural disaster event. In addition, domestic migration may lead to a shift in political powers at the state level, carrying national implications. As a result of the 2010 census, Louisiana lost a seat in Congress and one of their electoral votes. While not officially acknowledged as the cause of slowed population growth, it is possible and even probable that the 2005 hurricane season played a significant role in this demographic shift.[9] This has dramatic impacts on local, regional, and national economic success and subsequently on the ability of any place to be economically competitive.

Seltzer and Carbonell identified three key catalysts to regional planning across jurisdictional boundaries. One of those key motivators is associated "with natural or man-made disasters that far exceed the boundary of single jurisdictions."[10] We see planning for megaregional resilience to natural disasters as an extension of this regional planning theory. Resilience planning is gaining global momentum; the United Nations Sustainable Development Goals (SDGs) have woven resilience planning into multiple global includes, including goal 11 for sustainable cities and communities, and goal 17 for climate action.[11] In line with the SDGs, the researchers of this paper posit that impacts of natural disasters reach far beyond one region, and that the vulnerability of transport infrastructure to disaster risks is critical to regions or megaregions to return to a state of normalcy. Transport networks can either facilitate the flow of people and goods or inhibit them. If airports close, travelers can't get to end destinations. If railroads and roads are flooded, goods don't

[8] (Grenzeback, n.d.)
[9] (Times-Picayune, n.d.)
[10] (Armando Carbonell, 2011)
[11] ("Cities—United Nations Sustainable Development Action 2015," n.d.)

get transported long distances to people that may need them. If roads are inaccessible, emergency responders cannot easily reach people in need.

Last year, the researchers of this project evaluated the potential role of metropolitan planning organizations (MPOs) in megaregional planning to determine if MPOs could feasibly conduct megaregional planning based on existing regulatory frameworks. We investigated how transportation infrastructure is funded at state and MPOs levels and identified areas of constraints and opportunities for megaregional planning. Among the opportunities for voluntary collaboration that were identified, the researchers discovered that resilience planning for climate change and specifically to natural disasters was a natural extension of the megaregion conversation. We began this research project with the following question: What is the megaregional economic impact of a natural disaster? Moreover, how might you isolate the impact of the disaster among other potential causes of change or impact? Research in this field is relatively nascent and has expanded in recent years because of federal emphasis on the importance of economically connected regions. Data available at the megaregion level is largely nonexistent, with datasets created for analysis by aggregating county level data.

After conducting a brief survey of existing research to understand if and how a megaregional lens has been applied to evaluate transportation system resilience, the researchers found a need to create a foundational report that outlines primary questions and considerations of megaregional transportation resilience.

This report outlines existing funding mechanisms and federal resources available to state and regional agencies and evaluates the role of MPOs in transportation system resilience planning. It also includes an analysis of the resilience of three megaregions to natural disasters measuring indicators for population and employment. Information in the last chapter is presented as a reference guide for future research conducted on this topic. We created three-pager ‘resilience profiles’ for all 11 megaregions by synthesizing data and information from multiple sources for a quick reference.

This work is meant to serve as a scoping report that identifies questions in need of further research and data collection, because our initial overarching question led us to many other fundamental questions:

- How is economic impact typically measured post-disaster?
- How is the cost of transportation infrastructure evaluated?
- What are the primary risks that each of the 11 U.S. megaregions face, and how do those risks vary by megaregion in terms of transport planning?
- Are there spatial patterns that can be observed in terms of demographic changes after a natural disaster?
- Is there any pattern in how population disperses within a certain range away from the area of impact, and do those people subsequently return to the city they were forced to leave?
- Do MPOs have a vested interest in the recovery or resilience of MPOs in typically vulnerable areas?

Through the literature review and following chapters, we seek to answer the questions listed above. The following section provides the foundation for our research, and outlines both the rising importance of resilience to disaster events and climate change as well as the intersection of resilience planning with transport.

Chapter 2. Literature Review

The researchers of this report posit that resilience of transport systems is and will continue to be directly related to the economic competitiveness of an urban area, region, or megaregion. As natural disasters continue to increase in intensity and frequency, as effects of climate change impact our regions and states, government agencies at all levels will be forced to navigate and develop policy and funding sources to improve the resilience of transport systems and allow economic activity to resume speedily. As broader effects of climate change like sea level rise increase, urban and rural governments will increasingly be forced to grapple with trade-offs in infrastructure investments. Mitigation and adaptation form crucial building-block elements of preparing communities to deal with impacts of climate change. The sections below put transport systems in the context of natural disaster resilience and highlight the growing importance of making transport systems more resilient to short- and long-term impacts of climate change by identifying funding programs at the federal, state, and regional levels.

2.1 Defining Resilience

At this stage, it is imperative to define the word "resilience." The researchers of this report borrow from multiple referenced sources to determine the definition that guides out work. The United Nations (UN) defines resilience in cities as "the ability of any urban system to maintain continuity through all shocks and stresses while positively adapting and transforming towards sustainability. Therefore, a resilient city is one that assesses, plans and acts to prepare for and respond to all hazards, either sudden or slow-onset, expected or unexpected."[12] Making a city or urban system more resilient to shocks and stresses can be reached through strategies of climate mitigation or adaptation. Mitigation strategies work toward a goal of decreasing or preventing the emissions of greenhouse gases.[13] Adaptation strategies make changes based on anticipated and imminent changes, like changes in weather patterns resulting from global warming.[14] In a 2016 report, the Special Committee on Transportation Security and Emergency Management defined resilience as

[12] (UN Habitat, 2019)
[13] (United Nations, n.d.)
[14] (United Nations, n.d.)

"the nexus of preparing for the impacts of climate change while responding to the catalog of system vulnerabilities and emergencies".[15]

In 2012, researchers on two National Academy of Sciences (NAS) committees elevated the conversation on resilience planning by collaborating to produce a report called "Disaster Resilience: A National Imperative."[16] The report outlines the need for disaster resilience, defines how improvements in resilience can be measured, and identifies clear links between public and private infrastructure and how governments can work with communities to ensure holistic resilience improvements in communities around the country. The report considers overall economic impact to property and infrastructure, resident displacement, and disruption of business during the time of a disaster event. The federal government bill for disaster relief funding has steadily increased over the past 50 years as disaster events have increased in frequency and intensity. For example, after Hurricane Andrew in 1992 hit the south coast of Florida, the federal costs were recorded at $25 billion in 2017 dollars.[17] According to the Federal Reserve Bank of Atlanta, in a 2017 update "the town Florida City absorbed Andrew's most direct blow as the storm made landfall. The south Dade County town of about 12,000 saw 40% of its tax base obliterated, according to a report by the Miami-Dade County government. Florida City was poverty-stricken before Andrew and remains so today: 49% of its population lives below the federal poverty level, compared with 16% of all Floridians, according to U.S. Census Bureau data."[18] As a result of damages caused in Louisiana by Hurricane Katrina in 2005, the federal government paid over $48 billion in relief costs. The total costs were $108 billion.[19] The Federal Emergency Management Agency (FEMA) has paid out $81 billion to state, territorial, and local governments in response to natural disasters since 1992.[20] According to the Congressional Budget Office, average annual damage costs will increase to $39 billion for hurricane impacts by 2075.[21] In a press release after passage of the Disaster Recovery Reform Act of 2018 (DRRA, Division D of P.L. 115-254), FEMA noted a 2017 National Institute of Building Sciences Report that found "the nation saves

[15] (Fletcher & Ekern, 2016)
[16] (Committee on Increasing National Resilience to Hazards and Disasters, 2012)
[17] ("Hurricane Andrew, 25 Years Later—Federal Reserve Bank of Atlanta," 2017)
[18] ("Hurricane Andrew, 25 Years Later—Federal Reserve Bank of Atlanta," 2017)
[19] (Committee on Increasing National Resilience to Hazards and Disasters, 2012)
[20] (Amadeo, 2019)
[21] (Congress of the United States Congressional Budget Office, 2016)

six dollars in future disaster costs for every one dollar invested in mitigation activities."[22] Concentrating resilience efforts in anticipation of future disaster events is imperative to decrease the burden on suffering communities and mitigate potential risk, in addition to investing monetary resources at the forefront to decrease the need for post-disaster recovery funding.[23]

In light of the NAS report's findings, exploration of transportation system resilience at the geographic level of a megaregion is warranted. However, to understand how megaregional transport resilience planning could manifest, the research team investigated transport resilience concepts and how resilience planning currently takes place at various levels of governance. Information in the following sections provide the basis for that understanding.

2.2 Transport System Resilience Planning

Transportation infrastructure and transport ability serves multiple critical roles and risks during a natural disaster event. The vital need for effective and efficient transport systems during disaster times is unequivocal. Prior to a disaster, residents are typically instructed to evacuate areas that have potential to be harmed. Hurricane Rita in 2005 led to one of the largest evacuations in history in addition to an unprecedented level of gridlock of evacuees in Texas; some residents traveled about 200 miles over 24 hours.24 During a disaster transportation is also a critical asset to respond to the impacts as they are occurring. For example, fighting wildfires requires emergency services have access into neighborhoods using roads and corridors to both evacuate people and to also fight the fire.25 After a disaster, transport systems are also integral for connecting damaged areas and residents in need to necessary supplies. This could come in the form of providing medical supplies to hospitals, transporting displaced residents to temporary shelter, as well as rescuing any residents who did not evacuate at-risk areas. Functioning transport systems are also integral for anyone

[22] (FEMA, 2018)
[23] (Committee on Increasing National Resilience to Hazards and Disasters, 2012)
[24] This fact is anecdotal and from personal experience. One of the researchers of this report previously lived in Houston, Texas, and once spent about 24 hours evacuating to Waco for Hurricane Rita in 2005. Also supported by news articles referencing evacuation gridlock: (Levin, 2015); ("Hurricanes: Science and Society: 2005- Hurricane Rita," n.d.)
[25] For example, both directions of Topanga Canyon Road were shut down on Pacific Coast Highway and Mulholland Drive in California in a fire that broke out in heavy bush on November 16 2019. Day, Brian. *Firefighters Quickly Control Brush Fire in Topanga*. KTLA News. https://ktla.com/2019/11/16/brush-fire-ignites-in-topanga/

returning to their home or city post-disaster. Additionally, functioning transportation systems play a role in post-recovery activities for both the populace that has returned (for example, getting to and from work, school, doctor appointments, grocery shopping, and other trips) and for the logistics and supply chains that restock medicine, food, and retail goods and are integral to rebuilding or refurbishing buildings, infrastructure, utilities, and other critical life support systems in the very short term post-disaster.

Transport systems damaged from natural disasters require additional funding for maintenance, operations, and improvements to retrofit against future disasters (for example, raising a highway to a new high-water mark, or installing new drainage or pumping equipment in lower lying areas). Damage to infrastructure can have wide-ranging impacts, from inhibiting residents from re-establishing their communities to affecting national and international trade. This project hypothesized that impacts of natural disasters are also imposed on surrounding metropolitan area transport systems through additional infrastructure wear and tear due to population gain—whether temporary (as some residents of the disaster area may only temporarily remain in the metro area) or long term (as with newly relocated metro residents who do not return to their original home location). This population gain, not accounted for in traditional regional planning projections, could result in the need to upgrade or perform maintenance on transport systems faster than expected.

Ho and Hastak describe impacts to infrastructure as a primary impact of a natural disaster, with effects to industry categorized as secondary impacts.[26] This can result in supply chain disruptions through inability to access deliver points, delays in shipments, or loss of goods.[27] Because the transportation industry facilitates the functioning of other industries, damaged transport infrastructure can have disproportionately negative impacts on other industries that affect resident abilities to access healthcare, food, and necessary goods. Due to this constant vulnerability, transportation planning for disaster resilience should be widely integrated in transport planning practices to mitigate disruption of disaster events, and to reduce the impact of disasters on existing infrastructure.[28]

[26] (Ho & Hastak, n.d.)
[27] (Karagyozov, Razmov, Todorova, Varadinova, & Dzhaleva-Chonkova, 2012)
[28] (Rodrigue, Comtois, & Slack, 2017)

Rodrigue et al. believe that transportation disaster planning must be an ongoing and continuous effort for regions or megaregions to be adept to address potential future risks.[29] **Figure 2** illustrates the recommended process for integrating resilient practices into transport system planning, beginning with identifying system vulnerabilities and mitigating for those problems. This method is supported by existing federal pilot programs that fund projects to increase resilience of transport systems, highlighted in later sections of this report.

For the purposes of this report, "local" refers to urbanized areas and municipally managed infrastructure. "Regional" is used to describe metropolitan areas that may include one or more urbanized areas and may be made up of multiple counties. Megaregions are made up of multiple regions and may be connected by smaller urbanized areas or counties between regions.

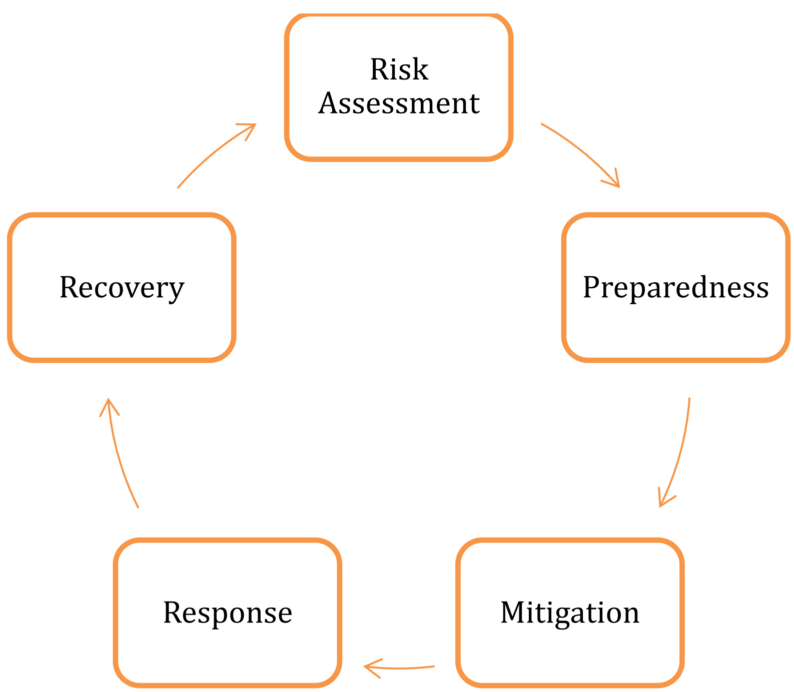

Figure 2: Transportation resilience.
(adapted from Geography of Transport)

[29] This figure is adapted from (Rodrigue, Comtois, & Slack, 2017)

Researchers at Louisiana State University (a CM^2 partner) evaluated the level of impact of shadow evacuations on the transportation network during natural disaster emergency evacuations.[30] Their research identifies the pain points of the transport network during times of high intensity and use, and can be integrated for future planning efforts at agencies coordinating evacuations prior to a disaster event. Researchers at Texas Southern University (TSU) (a CM^2 partner) are working on creating a rubric style decision-making matrix for transportation investments in a megaregion, and specifically identifying needs of vulnerable communities within a megaregion.[31]

In terms of natural disaster events, vulnerable populations can be at increased risk due to a lack of transportation options, among other factors. This risk is often heightened because land infrastructure is highly susceptible to damage; many people might not be able to evacuate a specific area due to age, health, and monetary constraints; and emergency supplies might not be readily accessible to populations in need post-disaster (due to lack of transport options, funding, and staffers to deliver these commodities). The work of researchers to identify increased risk to vulnerable populations from lack of transport connectivity will be crucial for regions to integrate transportation system resilience planning. Understanding vulnerabilities of the existing system will help transportation system planners and emergency response employees prepare for these considerations in resilience planning.

In 2008, the U.S. Department of Transportation (USDOT) kicked off the largest-scale resilience planning effort to date called the Gulf Coast Study. Stretching east to west from Galveston, Texas, to Mobile, Alabama, the first phase analyzed impacts of climate change on regional infrastructures. The study identified vulnerabilities of and risks to ports, road, transit, aviation, and rail infrastructure in the context of sea level rise and natural disaster occurrences.[32] USDOT developed a climate change sensitivity matrix, a tool to prioritize identified system vulnerabilities, and a climate data processing tool to project how climate change may affect transportation services in the future.[33] This effort sets an example for how transport agencies should collaborate across jurisdictional boundaries and provides precedent for federal support.

[30] (Wolshon, Herrera, Parr, & Zhang, 2018)
[31] (Lewis, 2018)
[32] (Federal Highway Administration, n.d.)
[33] (Federal Highway Administration, n.d.-d)

The concept of megaregions has gained popularity over the last two decades as a mechanism to recognize the interconnectedness of transportation systems, natural geography, and connections of regional economies. Recognizing megaregional systems and thinking on a broader scale than the metropolitan level allows regions to become economically competitive with other megaregions. The sections below address theories of economic resilience, outlines existing federal funding streams and mechanisms to increase transportation system resilience planning, provides examples of state and MPO best practices of applying federal funds, and explores the role that MPOs can play within a megaregion to move transportation system resilience planning forward.

2.3 Theories of Economic Resilience

Multiple theories and evaluations have been generated to determine and define economic resilience. Stefanie Oliva and Luciana Lazzeretti evaluated the economic resilience of Japan to natural disasters by conducting an analysis of major earthquakes. For the purposes of their research, they define resilience as "the amount of time required to reach a new normality after the occurrence of the disturbance."[34] They considered the ongoing debate of how to measure economic resilience and used the following indicators in the index they created for their evaluation of Japan's economic resilience. These included recovery in population, number of businesses, and gross regional product.[35] Oliva and Lazzaretti also address both the direct costs (such as damaged infrastructure that needs to be repaired immediately) and indirect costs of a disaster event. They note that indirect costs may be generated over a larger geographical area and may take longer to recover.[36]

Raghav Pant et al. evaluated static and dynamic measures for evaluating economic resilience of infrastructure systems.[37] Their work places a focus on the ability of infrastructure to recover and begin operating under the new state of normal, as the geographic area charts its path to return to pre-disaster conditions. The interdependence of infrastructure systems and the tremendous

[34] (Oliva & Lazzeretti, 2018)
[35] (Oliva & Lazzeretti, 2018)
[36] (Oliva & Lazzeretti, 2018)
[37] (Pant, Barker, & Zobel, 2014)

complexity of both pre-disaster planning and post-disaster damage evaluation is acknowledged by the researchers. Their work is meant to provide a framework to enable multiple and interdependent infrastructure industries to pre-evaluate and prepare for resource management in the event of an unanticipated shock to the system.[38]

Leabons et al. propose a set of indicators for evaluating the resilience of urban transportation systems.[39] The indicators proposed include network connectivity vulnerabilities, route capacity, mass transportation capacity, demand, travel time and distance post-event, alternative available routes, level of accessibility, alternative modes, time required to begin recovery, availability of people and resources to act, and the time required to restore normal operation or near it.[40] While the 11 indicators were proposed in considering urban transportation systems, the indicators have the potential to be scaled-up and considered in future evaluations of transport systems at the megaregion level for resilience to any and all disasters as well as to short-term or one-off shocks to transport infrastructure systems.

The methodologies described above were considered by the research team to create an approach to a preliminary analysis based on publicly available data. Chapter 4 of this report includes a case study of spatial resilience guided by the methodological approach used by Oliva and Lazzeretti.

2.4 Federal Programs and Incentives for Resilience Planning

The Fixing America's Surface Transportation Act (FAST Act), passed in 2015, is the most recent federal bill authorized for funding the nation's transportation system.[41] The FAST Act introduced an emphasis on the importance of transportation system resilience by expanding planning considerations and requiring strategies to reduce the vulnerability of existing transport infrastructure ([23 U.S.C. 134(d)(3) & (i)(2)(G)]).[42] The FAST Act expanded the list of MPO planning considerations to include improving transportation system resilience and reducing the

[38] (Pant et al., 2014)
[39] (Pant et al., 2014)
[40] (Pant et al., 2014)
[41] (Federal Highway Administration, n.d.-a)
[42] (Federal Highway Administration, n.d.-b)

amount of stormwater runoff of surface transportation. The same planning considerations were also expanded and included for application to statewide and non-metropolitan planning processes.[43] The bill included new language that requires MPOs to consider reducing the vulnerability of transportation system infrastructure to natural disasters in their capital investment strategies (23 U.S.C. 134(i)(2)(G)).[44] The addition of transportation resilience to natural disasters in the authorization bill symbolizes recognition by policy-makers of the role that transport plays before, during, and after a natural disaster event. This section below highlights federal agency programs, resources, and incentives for resilience planning and disaster relief related to transportation.

One of the most common mechanisms for funding disaster relief and restoration projects is the Robert T. Stafford Disaster Relief and Emergency Assistance Act 1988 (the Stafford Act) (42 U.S.C. Ch 68 §5121 et seq).[45] Funding is coordinated by FEMA, and serves as a primary resource of funds for state, local, and tribal governments after a Presidential Declaration of a natural disaster. Most of the federal funding available for transportation system recovery can only be used to restore segments of the transportation network to conditions that existed prior to the disaster.[46] This requirement realistically inhibits agencies from integrating more resilient strategies to recovery projects. However, most federal funding can be combined with other sources if an agency wants to restore transportation assets to higher standards for resilience to future disaster events.

Table 1 highlights federal government funding mechanisms for infrastructure repair following a natural disaster. The table identifies the name of the agency and program that administers funding, infrastructure types that the funds can be applied to, and specific conditions that must be met in order to be eligible for funding.

[43] (Federal Highway Administration, n.d.-c)
[44] (Federal Highway Administration, n.d.-b)
[45] ("Federal Funding Resources," 2012)
[46] ("Federal Funding Resources," 2012)

Table 1: Federal post-disaster transportation infrastructure funding.

Agency and Program[47]	**Infrastructure Type**	**Conditions**	**Presidential Declaration Required?**	**Authorized amount**
FHWA: Emergency Relief Program (23 U.S.C. §125).	Highways/roadways	Failure must be catastrophic in nature (a failure of the system causes "a disastrous impact on transportation services"). Failure must be external to the facility, and funding is not expected to cover the full cost of the improvement. States must apply on behalf of local transportation agencies. Money can go to states, and states decide if funding will be provided for locally owned or state-owned federal aid highways.	No	$100 million annually
FHWA: Emergency Relief of Federally Owned Roads (23 CFR 668 Subpart B).	Federal roads (roads providing access to and within Federal and Tribal lands).	Funding is meant to repair roads damaged from a catastrophic and external event back to pre-disaster conditions. Funding can be used for repair or reconstruction of federal roads.	No	No ceiling
Federal Transit Administration (FTA): Emergency Relief Program (49 U.S.C. §5324) authorized under FAST Act.	Transit	Can provide emergency assistance but requires Congress to make supplemental appropriations to FTA. Allows agencies that serve less than 200,000 people to use FTA capital funds for operations in response to an emergency event. Otherwise, in rare cases and on a case-by-case basis, could allow local agencies to defer their local match that is typically required to receive FTA funds.	No	No ceiling, but no allocation annually

[47] https://www.transportation.gov/highlights/disaster-recovery/funding/federal

Agency and Program[47]	Infrastructure Type	Conditions	Presidential Declaration Required?	Authorized amount
FRA: Railroad Rehabilitation & Improvement Financing (RRIF) authorized by Transportation Equity Act for 21st Century (TEA-21) Public Law 105-178. 1998	Railroad	Railroads, state and local governments, government-sponsored authorities and corporations, joint ventures with at least one railroad, and some freight shippers who intend to build a new rail connection. The funding must be used to create new railroad facilities, rehabilitate and enhance existing facilities, acquire new facilities, or to refinance outstanding debt for rehabilitation and acquisition-related projects. The program is not designed for emergency recovery but can be used in this case for supplementary funds.	No	Up to $35 billion.[48]
FAA: Airport Improvement Program (Established through Federal Order 5090.5)	Airports that are part of the National Plan of Integrated Airport Systems	Airport must be part of the National Plan of Integrated Airport Systems. The Airport Improvement Program is not a dedicated funding source for natural disasters. The program is used to improve airport conditions, including safety, capacity, etc. This program typically only provides extra funds for emergency management after a specific appropriation from Congress. Owners of airports can be public or private.	No	$157 million awarded in 2019.[49]

[48] ("Federal Funding Resources," 2012)
[49] ("Press Release – U.S. Transportation Secretary Elaine L. Chao Announces $157 Million in Infrastructure Grants to 34 Airports in 19 States and One Territory," 2019)

Other federal agencies that offer grants or funding for hazard mitigation or recovery include the Department of Homeland Security, Housing and Urban Development, U.S. Small Business Administration, U.S. Department of Commerce, the Public Works and Economic Development Program, and the Economic Adjustment Assistance Program.[50]

The following subsections provide examples of how states and MPOs have integrated resilience planning into their work and identify the role that federal funding played within the effort.

2.5 State-level Resilience Planning Case Studies

When a natural disaster event prompts a Presidential Declaration, states are eligible to receive Public Assistance grants and FEMA funds for recovery.[51] States typically also have a fund dedicated to disaster emergencies, which are used for recovery efforts or the 25% match required for Public Assistance grants. When a natural disaster prompts a Governor's Declaration and not a Presidential Declaration, any existing state disaster recovery fund can only be accessed after all local and county-level disaster recovery funds have been used toward recovery efforts. Not all state and federal agency departments follow this rule for appropriation of funding post-disaster infrastructure improvements. The FHWA, for example, has an emergency relief fund that can be accessed without a Presidential Declaration.[52]

Table 2 was created using case studies identified by USDOT as best-practice examples of state agencies leveraging public funds for post-disaster recovery and resilience efforts. Examples in the table range from a state transportation commission proactively allowing appropriation of funding in emergency situations to a state department of transportation (DOT) identifying a vulnerable asset and replacing it prior to a natural disaster event. Other examples include how agencies leveraged multiple funding sources to meet the repair needs of their transportations system resulting from natural disaster events and man-made climate change. The table highlights how broad and inclusive the category of disaster-recovery and resilience efforts can be.

[50] ("Federal Funding Resources," 2012) https://www.transportation.gov/highlights/disaster-recovery/funding/federal
[51] (U.S. Department of Transportation, n.d.)
[52] (U.S. Department of Transportation, n.d.)

Table 2: Examples of state agencies that leveraged federal funds for transportation recovery projects.[53]

State	Funding Source	Types of Natural Disaster Events	Best Practice Example
California	Special Fund for Economic Uncertainties, Disaster Assistance Fund, CDOT funding.	Storms, Flooding, Landslides	The California Transportation Commission signed a resolution to allow appropriation of funding to post-disaster projects without waiting for the formal body to meet. This allows state agencies to combine funds from multiple sources and enables them to comprehensively address a recovery project at the outset as opposed to finding a temporary fix.
Iowa	Combination of grants from USDOT, FEMA, state and bond funds.	Series of floods, tornados, and severe thunderstorms within four months.	The statewide recovery plan includes a framework for how to address transportation needs post-disaster for both emergency needs and infrastructure repair. The state also leveraged multiple funding sources to fund projects at a faster rate.
Louisiana	State Emergency Relief Fund, regular appropriations of disaster funds.	Hurricanes	Proactively improved a roadway that would have been extremely vulnerable in a next potential disaster event. The DOT replaced the roadway infrastructure with more resilient materials.
Kansas	State Emergency Fund.	Tornado; demolished 90% of structures in Greensburg, Kansas.	The community used this unfortunate occurrence and need for a long-term recovery plan as an opportunity to re-envision and rebuild the town around a critical link of transportation infrastructure. The new vision will be developed around the rebuilding of this road (US 54) to minimize displacement of residents and homes.
Wisconsin	Wisconsin Disaster Fund.	Floods	Combined efforts for transportation system recovery and economic development efforts to fund improvements to a town damaged by a flooding event.

[53] For more info: For more detail about these case studies see reference: (U.S. Department of Transportation, n.d.)

2.6 The Role of MPOs in Resilience Planning

The role and significance of MPOs can vary by state or region. Federal regulations for MPOs provide flexibility within the parameters of federally required work products. Some state DOTs provide additional guidance through regulatory requirements or financial support through competitive grants. Since the authorization of the FAST Act, MPOs have integrated resilience planning into their work by developing climate adaptation and mitigation strategies and integrating the strategies into the project prioritization processes, among other methods. The long-range nature of an MPO's work makes addressing effects of man-made climate change and resilience to natural disasters integral to achieving effective regional outcomes. In some megaregions like Southern California and Northern California, MPOs are contiguous through all or most of the identified megaregion, necessitating coordination and collaboration of outcomes and goals. In other megaregions like Southern Florida, there are pockets of contiguous MPOs within the megaregion.

The Southern Florida Megaregion has begun to indirectly address resilience planning for transportation systems on a regional scale, and MPOs have initiated conversations about coordination needs at a larger geographic scale. Acknowledging the need for coordination across MPOs and across regions, the Tampa Bay Area Regional Transit Authority (TBARTA) conducted a study over several months to determine best practices and strategies for regional coordination across the Tampa Bay region.[54] The state of Florida has varying and prominent needs for resilience planning because of its coastal centers of population. The Sarasota/Manatee MPO and Hillsborough MPO[55] participated in a training workshop for an All Hazards Recovery Plan, part of a national pilot project sponsored by FTA, the national Association of Metropolitan Planning Organizations (AMPO), and Portland State University researchers. A two-day workshop was convened to equip MPO leaders with tools to integrate long-range resilience planning best practices into their planning processes.[56]

[54] ("Other Regional Plans & Projects," n.d.)
[55] TBARTA includes Manatee and Hillsborough MPO regions among others and serves about 2.4 million people.
[56] This information also came from an informal interview with the Executive Director of the Sarasota/Manatee MPO in March 2019.

The Sacramento Area Council of Governments (SACOG) is currently working on a second iteration to a Climate Adaptation Plan.[57] With state DOT funding to support the second stage of this plan, SACOG can conduct a more fine-grained analysis to evaluate the vulnerability of different assets and segments of the transportation system.[58] SACOG plans to evaluate all projects within the long-range metropolitan transportation plan and integrate the results of the vulnerability assessment into feedback on project proposals to local agencies. This could lead to SACOG requiring local agencies to mitigate for identified vulnerabilities, or letting the local agency decide how to change the project in order to make it the most competitive for regional funding. The effort to improve climate adaptation strategies in northern California is a subset of a broader joint effort by researchers from multiple universities, the state DOT (CalTrans), Google, and other technical agencies. This consortium of partners created Cal-Adapt, a resource that provides tools, data, and other forms of climate-projection information for use of the California research community.[59] It provides geographic visualization of extreme precipitation events, extreme drought scenarios, sea level rise, wildfire projections, and streamflow, among other categories.[60] The presence of a statewide tool enables all regional and local agencies to work with uniform sets of data projections, which can enable working across regions with this data in the future. The tool also provides a foundational resource for SACOG to pursue its initiative to create a vulnerability assessment framework within the greater Sacramento region without having to create a new tool to get started.

While the climate adaptation study is not being pursued on a megaregional scale, the indisputable relationship between residential and work locations with neighboring MPOs in the Northern California Megaregion keeps them inextricably linked. For example, MPOs surrounding the Bay Area MPO tend to have higher commuting times and congestion because San Francisco employees tend to live outside of the city. San Francisco has low availability of housing compared to the number of jobs that draw people into the city, creating longer commuting patterns for workers who

[57] SACOG serves a region of approximately 2.2 million residents, 6 number of counties and 22 cities. ("About SACOG," n.d.)
[58] Learned through an informal interview with a SACOG Program Analyst in March 2019.
[59] (California Energy Commission & University of California, Berkeley, 2019)
[60] (California Energy Commission & University of California, Berkeley, 2019)

live outside of the city. MPOs like SACOG consider this to be a megaregional problem, and not a regional problem constrained to the MPO boundaries.[61]

In Southern California, the Southern California Area Governments (SCAG) identified numerous goals related to man-made climate change in the 2012–2035 Regional Transportation Plan/Sustainable Communities Strategy. The plan also includes guidelines for local agencies to assess vulnerabilities of existing systems and to develop climate adaptation strategies. It identifies opportunities to integrate climate change planning into transit planning, procurement, and transit asset management. SCAG provides multiple resources for local agencies for climate change transit planning, specifically regarding how to obtain reliable and reputable projection data, how to address system vulnerability, the prioritization processes, and how to determine the criticality of different needs. Determining criticality is based on a ranking system between threats to assets and service provision. Some examples of adaptation strategies involve enhancing redundancies in areas most vulnerable to system disruptions, and to increase drainage of flood protection features around assets.[62] Because SCAG is the largest MPO within the Southern California megaregion, implementation of this plan can have a disproportionate impact on the megaregion and can serve as a cornerstone example to guide smaller surrounding MPOs in planning for resilient transportation systems.

The role of an MPO in resilience planning may vary across megaregions based on different state regulations and levels of support. Based on federal regulations, all MPOs are required to consider resilience planning in the list of federally provided planning considerations during long-range plan development and project selection. Without additional state support, some larger MPOs could take initiative to integrate resilience to natural disasters and climate change mitigation or adaptation into prioritization processes. Without additional funding or resources made available by federal or state governments, partnerships with research universities and private entities for data collection and analysis might be integral to the ability of MPOs to begin implementing resilience planning.

[61] This insight came from an informal interview in March 2019 with a Program Analyst at SACOG who works on the climate adaptation plan.
[62] (Southern California Association of Governments, 2012)

2.7 Evaluating Economic Impact

To test how we might evaluate economic impact at a megaregional level, we chose to focus on the impact of Hurricane Harvey. The first step included identifying methods and sources used to calculate economic impact. We discovered that different methods were used by various agencies, resulting in sometimes drastically different numbers. For example, an early assessment of Hurricane Harvey's impact on vulnerable Texans in the Gulf Coast Region quotes damage "as high as $190 billion".[63] This news article mentions three loss estimates, ranging from $65 billion to $180 billion and $190 billion. The $65 billion loss estimate produced by AIR Worldwide includes damage to all properties eligible for coverage regardless of whether they are insured and without any application of deductibles or limits. AIR's property loss estimates for flooding capture losses for onshore residential, commercial, and industrial properties and their contents, automobiles, and time element coverage (additional living expenses for residential properties and business interruption for commercial properties; the estimates do not, however, include contingent business interruption losses resulting from the closure of oil refineries in the region). The $190 billion loss estimate produced by AccuWeather includes disruptions to businesses, increased unemployment rates for weeks and possibly months damage to transportation infrastructure, crop loss, increased gasoline and fuel prices, damage to homes/cars/furniture/antiques, and loss of valuable papers and cherished belongings. The $180 billion loss estimate is directly from Governor Greg Abbott, cited in multiple news articles. [64] The methodology on how this estimate is derived is unknown. A separate progress report developed by the City of Houston provided the following damage estimates: $16 billion in residential damage, $2 to $3 billion in damage to over 400 city-owned buildings, water/wastewater facilities, roads, bridges, and public utilities.[65]

We also compared damages recorded by the Houston-Galveston Area Council (H-GAC), the National Oceanic and Atmospheric Administration (NOAA), and FEMA. **Table 3** provides a summary of the tools used to derive damage estimates, as well as identified inputs and outputs.

[63] (Irfan, 2017)
[64] (Hamel, Wu, Brodie, Sim, & Marks, 2017)
[65] (City of Houston, 2018)

Table 3: Summary of three different agency damage estimate methodologies.

Entity	Method	Input	Output (Loss)
H-GAC	HAZUS	**Type of hazard**: earthquake, flood, wind **Inventory**: Building stock (residential and commercial), critical facilities, transportation (oil pipe, gas pipe, highway, railroad), utility, demographics	**Economic**: direct loss and business intervention **Social**: shelter and casualties **Functionality and debris:** damage to essential facilities, emergency response, transportation, and utilities **System performance:** water, power, transportation
NOAA - National Centers for Environmental Information	Uses insurance data to extrapolate uninsured losses, and account for non-insured government disaster assistance to calculate total costs associated with a disaster.	**Insurance data:** FEMA/National Flood Insurance Program, ISO/Property Claim Services, USDA/Risk Management Agency	Insured losses and uninsured losses for buildings and the agriculture sector
FEMA	Hazard Mitigation Plan–Risk Assessment Guide (using Hazus in combination with other data)		**Structure loss:** replacement value based on present-day cost of labor and materials **Content loss:** percentage of building value that varies by the type of building **Function loss**: lost revenue for public works and private entities estimated from operating budget and national average annual sales.

In searching for a measure of economic impact specific to transportation infrastructure, the Texas Legislative Budget Board[66] issued a report on the fiscal impact of Harvey for state agencies. This

[66] The Legislative Budget Board (LBB) is a permanent joint committee of the Texas Legislature that develops budget and policy recommendations for legislative appropriations, completes fiscal analyses for proposed

report stated that the Texas DOT (TxDOT) reported approximately $96 million in Harvey-related expenditures. Further information could be found on TxDOT's website regarding the improvements that these funds were spent on.[67]

All economic data that we discovered was calculated using a range of different methodologies. The most valuable insight that was gained was the level of complexity in trying to estimate the economic impact of transportation infrastructure damage at a regional level, a geographic level where ample data and information is already collected and recorded. It illustrated the major difficulty in trying to estimate economic damages at the megaregion level with existing data and economic estimates. As seen in Chapter 5, few megaregions are made up of contiguous adjacent metropolitan regions; disparities exist between the level of information available at the metropolitan level compared to the county or municipal level. The research team endeavored to find information related to the cost of damages specific to transport infrastructure and the share of funding contributed by MPOs during the recovery phase of Hurricane Katrina and Hurricane Harvey. We were unable to identify the amount of funding that MPOs directed toward repairing regional transport infrastructure. Moreover, there was not a clear path to track federal funding that would have been reimbursed to a transit agency or MPO in these two metropolitan areas. Economic impact costs were often aggregated to include cost of impacts to all infrastructure. Based on publicly available documentation, it was not possible to decouple transport estimates from other infrastructure types. Lastly, economic impacts to transport infrastructure and government agency will vary widely based on jurisdiction. A metropolitan region includes federal highways, local and county-owned infrastructure, regional transit services, and more. The web of jurisdictional overlap complicates the ability to identify economic impact of a disaster specific to transport infrastructure.

Our team decided to focus on the aspects that we considered the biggest gaps in existing literature: understanding the role that different federal agencies play in resilience planning for transport infrastructure, and providing a foundational reference tool to understand the issues that each individual megaregion will be forced to confront in terms of climate change concerns and natural disaster events. The following chapter focuses on available federal resources and tools available.

---

legislation, and conducts evaluations and reviews to improve the efficiency and performance of state and local operations.

[67] (Legislative Budget Board, 2018)

Chapter 3: Resources & Data

The topic of transportation planning resilience and broader climate mitigation and adaptation for transportation infrastructure requires cross-disciplinary and cross-agency resources. The U.S. government has multiple agencies that work on related aspects of climate change mitigation and adaptation and resilience planning, including USDOT, U.S. Environmental Protection Agency (EPA), NOAA, and FEMA. Each of these departments have divisions that focus on niche aspects of the conversation. One eye-opening aspect of this research was the number of agencies and resources available on this topic, and the level of complexity required in knowing how to navigate locating existing information for research. The following sections outline the roles of each of the government bodies as it relates to this work, and the data that may be most useful for future research needs.

3.1 National Oceanic and Atmospheric Administration

The National Centers for Environmental Information (NCEI) is a branch of NOAA that calculates and tracks costs of severe weather and climate events. This information is collected to provide historical records of societal and economic impacts of climate-related events. NCEI maintains an analysis focused specifically on billion-dollar disasters that effect the United States, including hurricanes, droughts, inland floods, severe local storms, wildfires, crop freeze events, and winter storms.[68] Between 1980 and July of 2019, the United States had 250 disaster events, totaling a cost of $1.7 trillion (**Figure 3**).[69] Of that cost, 68% occurred in the 170 events between 2000 and 2019. Tropical cyclones have caused the most damage, are responsible for the highest number of deaths, and cost more on average than other storm events. Severe storms are the most frequent type of billion-dollar disaster event and rank the third highest in terms of number of deaths but have a lower average cost per event. Flooding events are the third most frequent type of events, followed by droughts. Droughts and heat waves rank second in responsibility for highest number of deaths, following tropical cyclones.

[68] (National Centers for Environmental Information, n.d.-b)
[69] (National Centers for Environmental Information, 2019)

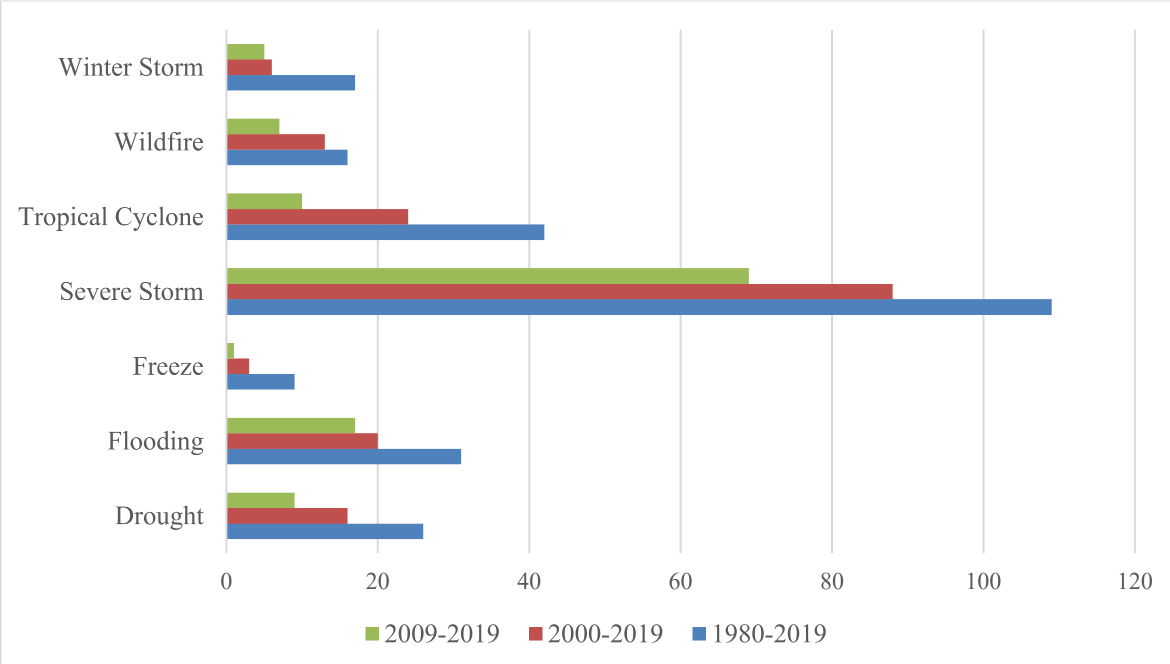

Figure 3: Number of U.S. billion-dollar disaster weather events between 1980 and 2019.[70]

3.2 U.S. Department of Transportation

The FHWA's Environment Division helps state and regional transportation agencies plan for sustainable transport systems. The goals that this division assists with includes emissions reduction, improved sustainability, and increased resilience of systems and assets. In a presentation given during AMPO's 2018 annual meeting, an FHWA official with the Office of Natural Environment highlighted changes in federal regulation that encourage regional agencies to integrate resilience into transport planning practices. Asset management plans and long-range metropolitan transportation plans should consider risks of environmental conditions and reduce vulnerabilities to existing and future natural disaster risks.[71] Additionally, assets that have required repeated repair over time must go through an analysis of alternative options, saving agencies future time and investment in highly vulnerable infrastructure.[72] This division creates tools to provide assistance to transportation agencies to integrate resilience into ongoing transportation planning cycles and processes. The division also facilitates workshops and provides policy guidance for agencies seeking to integrate sustainability practices into planning and investment practices. They

[70] (National Centers for Environmental Information, 2019)
[71] (Holsinger, 2018)
[72] (Holsinger, 2018)

offer a climate data processing tool, a sensitivity matrix, and a resource for scoring the vulnerability of assets as well as guidance for assessing the criticality of an asset within the broader system.[73] Their pilot programs for developing the vulnerability and adaptation frameworks were used to create megaregional resilience reference pages in Chapter 5. The Bureau of Transportation Statistics also collects statistics related to transportation and the economy, commodity flows, energy consumption of transportation systems, movement of freight, airline passenger volumes, port performance, and transportation statistics at the federal and state levels, among other aspects of transportation.[74]

3.3 Environmental Protection Agency

The U.S. EPA is a regulatory body that protects human health and the environment.[75] The EPA regulates compliance with policies related to hazardous waste and materials, drinking water, air pollutants that affect human health, chemicals and toxic substances, greenhouse gas emissions, sustainable energy, transportation, and food waste and recycling.[76] The major points of intersection with transport resilience planning is the EPA's work on air quality, greenhouse gas emissions, the effects of pollutants on human health, and sustainable energy and transportation choices. The agency provides resources for how government agencies and operators can decrease their greenhouse gas emissions and local air pollutants and provides tools to monitor the output of pollutants and programs to incentivize cleaner vehicles. The EPA is a frequent partner on inter-agency projects related to reducing emissions and increasing long-term resilience of communities. For example, the EPA partnered with FEMA to work with multiple California MPOs to create the *Regional Resilience Toolkit*.[77] Using a five-step plan, the toolkit empowers local and regional government agencies to work together at a regional scale to enhance hazard resilience across jurisdictions. The toolkit also provides an avenue for community groups and nongovernmental agencies to participate. The toolkit has been used in three California regions at the time that this report was written. Climate mitigation and adaptation strategies are closely related to the work that the EPA drives forward on a regular basis.

[73] ("Tools—Resilience—Sustainability—Environment—FHWA," n.d.)
[74] ("Bureau of Transportation Statistics," n.d.)
[75] (OA US EPA, 2013)
[76] (OEI US EPA, 2016)
[77] (OA US EPA, 2019)

3.4 Federal Emergency Management Agency

FEMA, created in 1979[78], has the mission of "helping people before, during, and after disasters."[79] The agency prepares preliminary damage assessment reports from year to year for major disaster declarations by state, provides assistance for individuals for relief post-disaster, and provides hazard mitigation planning assistance in advance of storm events. FEMA also sets up local disaster recovery centers for disaster survivors to access for help. FEMA has a toolbox of information for reporting such as reports for individual disaster events that can be located by year or state and provides a collection of resources related to climate change, including the *U.S. Climate Resilience Toolkit*. FEMA manages and has created multiple resources for state, regional, and local agencies, including a national flood insurance program, flood hazard mapping, a stormwater calculator, and tools to identify the level of risk of disaster threats and sea level rise. FEMA has been working on an inter-agency effort to develop national indicators to measure community resilience.[80]

FEMA also developed Hazus, a software utilizing nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes. Hazus uses geographic information systems (GIS) technology to estimate the physical, economic, and social impacts of disasters. *Physical damage* refers to residential and commercial buildings, schools, critical facilities, and infrastructure. *Economic loss* includes lost jobs, business interruptions, repair, and reconstruction costs. Lastly, *social impacts* include estimates of shelter requirements and displaced households.[81]

The following section includes an initial analysis of spatial resilience based on Oliva and Lazaretti's methodology highlighted in the literature review.

[78] ("Executive Orders," 2016)
[79] (Federal Emergency Management Agency, 2019a)
[80] (Federal Emergency Management Agency, 2019c)
[81] (Federal Emergency Management Agency, 2019b)

Chapter 4: Case Study of Spatial Resilience

This chapter mimics part of the methods used in Oliva and Lazaretti's study and evaluates population and employment information, including a geospatial analysis of resilience to hurricanes for the three megaregions that border the Gulf of Mexico: Texas Triangle, Gulf Coast, and Southern Florida (Figure 4).

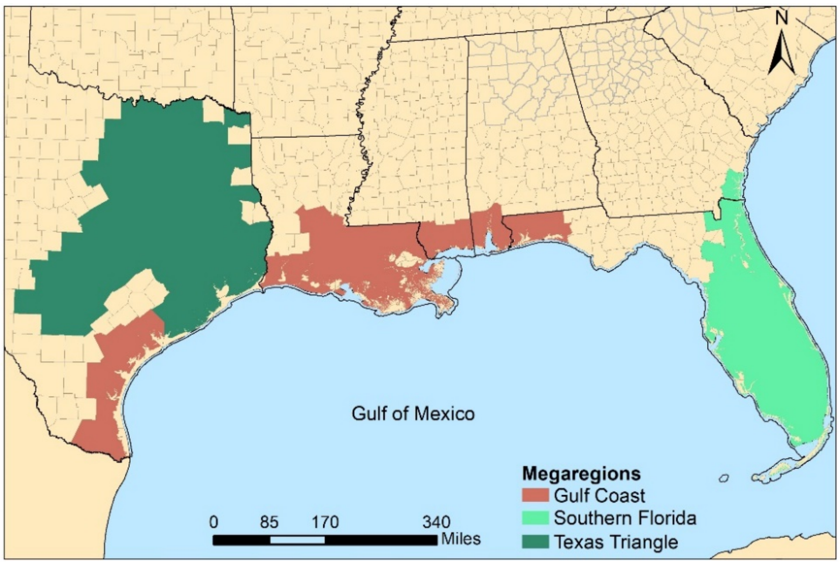

Figure 4: Three megaregions included in this analysis: Texas Triangle (dark green), Gulf Coast (red), and Southern Florida (green).

The World Economic Forum (WEF) defines economic competitiveness as "the set of institutions, policies and factors that determine the level of productivity of a country".[82] Since 1979, the WEF has been tracking indicators related to productivity of different economies, with the belief that productivity has a strong relationship with the well-being of an area's residents.[83] WEF tracks indicators of productivity; transport infrastructure is one of two subgroups in the category of infrastructure indicators that include roads, rail, aviation, and maritime transport.[84] While the WEF tracks economic competitiveness at the national level, the organization has acknowledged the importance of evaluating economic competitiveness on a regional scale around the world. The researchers of this report argue that understanding economic competitiveness at a regional scale is

[82] (Cann, 2017)
[83] (Cann, 2017)
[84] (World Economic Forum, n.d.-b)

essential to applying the concept to the megaregional level. WEF noted that, "Understanding priorities and determinants of economic competitiveness across regions will enable regions to chart a path toward decisions that impact the future of economic growth and competitiveness over time."[85]

Economic competitiveness is a foundational element of megaregional theory. Resilience is also closely tied with economic competitiveness. Cities or communities that are more resilient to unplanned disruptions may be more likely to have less vulnerable economic systems that can recover to pre-disaster levels. Resuming the regular activities of moving goods and people ultimately generates economic activity. This study considers megaregions surrounding the Gulf of Mexico because coastal communities are highly vulnerable to tropical storm and disaster events.

Research questions driving this case study include:

- How resilient are the Texas Triangle, Gulf Coast, and Southern Florida Megaregions to natural disasters with regard to population and total employment?
- How long did it take for each megaregion to restore population and total employment levels prior to the natural disaster event?

4.1 Methods and Data Sources

The evaluation considers the implications of the geospatial analysis findings on the megaregional transport system. The timeframe of the analysis is 2001 to 2017. This chapter evaluates megaregional resilience to hurricanes by analyzing the amount of time that passes before indicators return to pre-disaster levels. County-level data is aggregated to the megaregion level for this assessment.

Population and economic profile data at the county level were downloaded from the Bureau of Economic Analysis (BEA). Economic profile information used in this report includes the total number of employed persons in a county. Population estimates were joined to TIGER shapefile

[85] (World Economic Forum, n.d.-a, p. 3)

data, downloaded from the U.S. Census Bureau website to show the geospatial change in population after one natural disaster in each megaregion.

Geographic information for megaregions was downloaded from the America 2050 RPA website.[86] The shapefile included all 11 megaregions; individual shapefiles were created for each megaregion based on a query of megaregion name. This information was exported to create an Excel spreadsheet for data analysis based on the counties in each megaregion. Information was downloaded to collect the number of counties in each megaregion, as well as future population estimates included in the shapefile. The counties included in these shapefiles were used to separate out demographic information, which is produced by BEA at the county level for each state. Information was then aggregated to be reflected at the megaregion level. For the specific years where population change is shown geospatially, population change for the year before and after the specified disaster was subsequently calculated.

Hurricane data was found on the NOAA website, and subsequently manually logged and summarized for the number of hurricanes that occurred between 2001 and 2017 in the Gulf of Mexico that made landfall in one of the three megaregions. The hurricane information was transcribed from the NOAA hurricane tracker. The query used to identify hurricanes in the Gulf of Mexico within a specific timeframe included selecting "Gulf of Mexico" in the ocean basin dropdown and selecting advanced filters for hurricanes that were reported as Category 1–5. The information included in this report includes category of hurricane during the time of initial land contact. Some hurricanes made contact with land more than once or progressed to states north of the identified megaregions in their later stages, often as they declined in intensity. Hurricane information was transcribed and manually categorized by megaregion based on location of landfall and primary location and impact. Note that Hurricane Harvey is listed as taking place in the Gulf Coast Megaregion, though the storm is known for its devastating impacts to the Houston metropolitan area (which falls into the Texas Triangle Megaregion). For the purposes of this report, if a hurricane ultimately downgraded into a tropical depression, the megaregion impacted by the tropical depression is not categorized or noted.

[86] (Regional Plan Association, 2016)

4.2 Analysis

Hurricanes tend to cover wide areas and move slowly, although they are associated with high winds and rainfalls.[87] A hurricane can have extensive damaging effects on land transportation, and temporarily suspend all operations of maritime, air, and rail or public transit operations. These closures have impacts on daily commuting patterns, economic ramifications for the delayed flow of goods, and impacts on how needed emergency relief may be able to access areas and people in need. Rodrigue et al. cite four major issues of disasters relevant to national security, including the restricted ability or potential inability to 1) respond to national security needs, 2) deploy emergency relief or necessary troops, 3) reduce vulnerability of people and infrastructure systems, and 4) prevent illegal activities during a disruption.[88] Hurricanes make landfall at varying levels of intensity, and hurricane categories are identified based on sustained wind speed at the time of designation.[89] The Saffir-Simpson Hurricane Wind Scale is a widely used rating scale of 1 to 5. The rating and category hurricane designation is meant to communicate the anticipated intensity and potential damage to property or life.[90] While all tropical cyclones that upgrade to receive hurricane designations and ratings are dangerous, categories 3 through 5 are considered major hurricanes.[91] A table of hurricane intensity and designation created by the National Hurricane Center (part of NOAA) can be found in **Table 4**.

[87] (Rodrigue, Comtois, & Slack, 2017)
[88] (Rodrigue, Comtois, & Slack, 2017)
[89] (National Hurricane Center, 2019)
[90] (National Hurricane Center, 2019)
[91] (National Hurricane Center, 2019)

Table 4: Level of damage anticipated by Saffir-Simpson scale category.[92]

Category	Sustained Winds	Types and Level of Damage Due to Hurricane Winds
1	74 – 95 mph 64 – 82 kt 119 – 153 km/h	**Very dangerous winds, will produce some damage:** power outages may last up to a few days.
2	96 – 110 mph 83 – 95 kt 154 – 177 km/h	**Extremely dangerous winds will cause extensive damage:** close to total power loss expected, outages could last up to multiple weeks.
3 (major)	111 – 129 mph 96 – 112 kt 178 – 208 km/h	**Devastating damage will occur:** damage to framed homes; electricity and water likely unavailable after storm passes.
4 (major)	130 – 156 mph 113 – 136 kt 209 – 251 km/h	**Catastrophic damage will occur:** most of the area will be uninhabitable for weeks or months.
5 (major)	157 mph or higher 137 kt or higher 252 km/h or higher	**Catastrophic damage will occur:** most of the area will be uninhabitable for weeks or months.

Information presented in the findings includes a comparison of projected population and employment numbers for the megaregion between 2000 and 2020 as created by the RPA, and actual numbers of population and employment between 2000 and 2017. A map is provided for geographic reference of each megaregion, and subsequent maps are included to show population distribution and change at the county level for a specific natural disaster event. A table of hurricanes that made landfall in each megaregion is also included in the findings, as well as a map identifying counties that never recovered pre-disaster levels of population or total employment.

The America 2050 initiative included population projections for all megaregions to the year 2050. Employment projections were also created out to the year 2025. For reference of the findings of the RPA report, the estimated projections are provided in **Figure 5** and **Figure 6**.

[92] (National Hurricane Center, 2019)

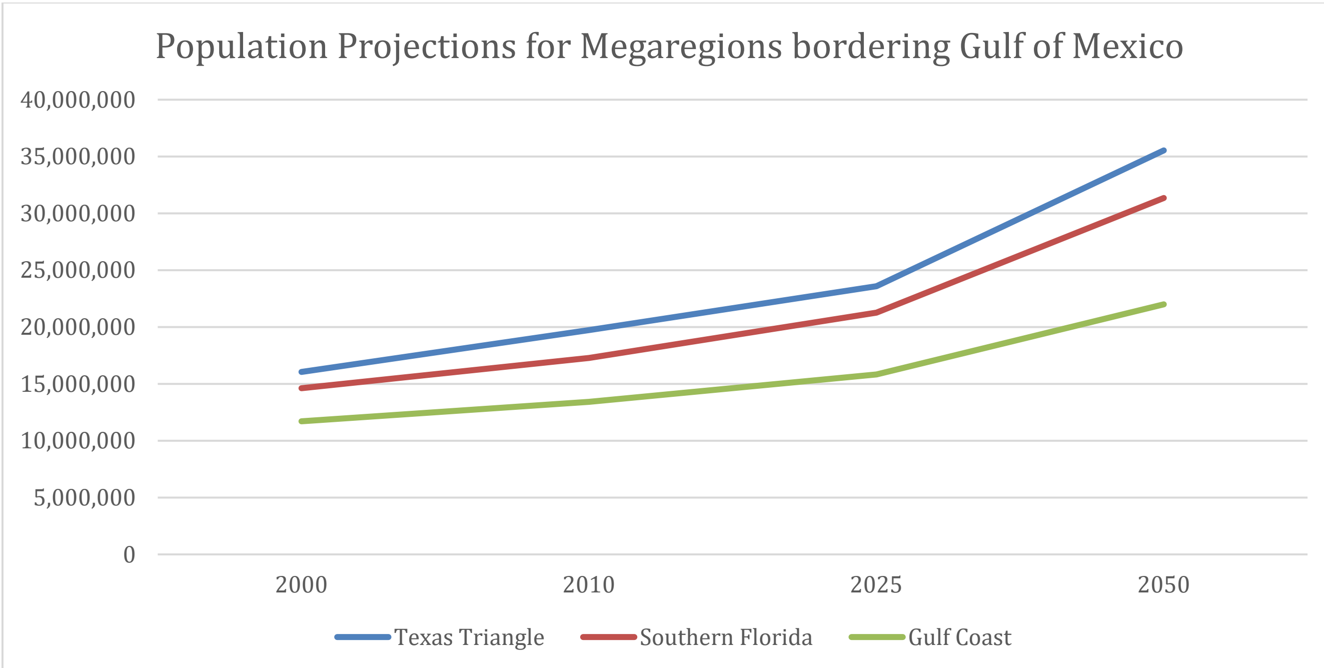

Figure 5: Population projections for Texas Triangle, Southern Florida, and Gulf Coast Megaregions.
(Source: RPA)

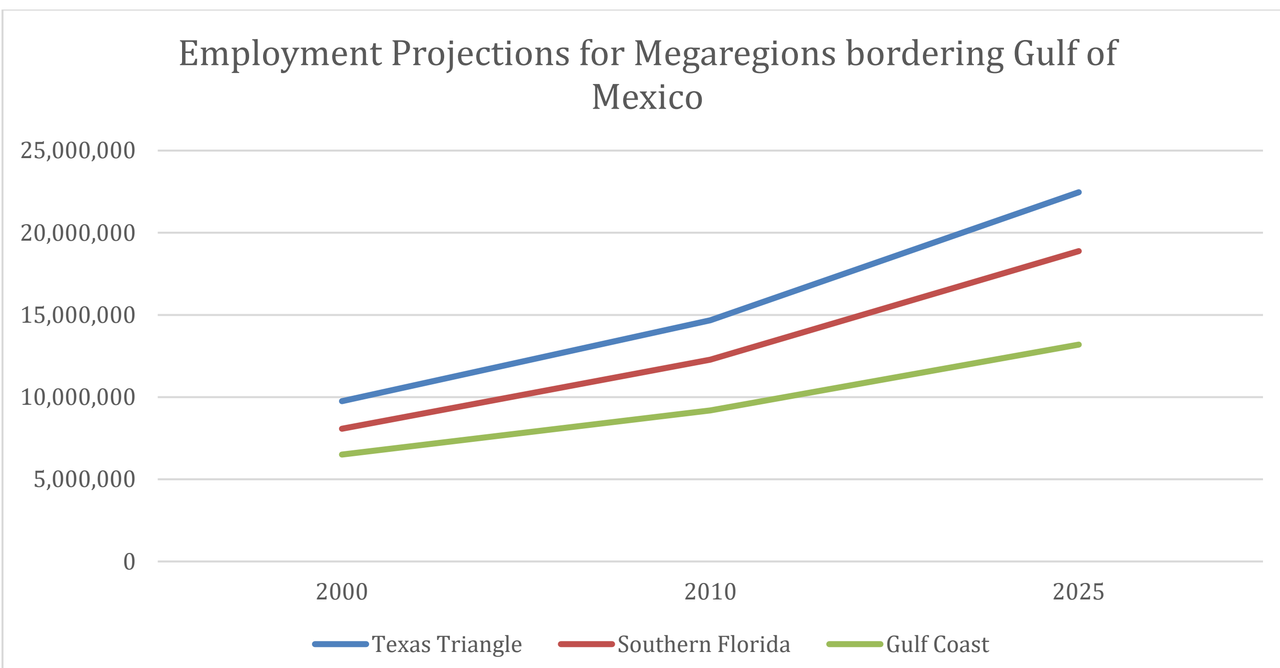

Figure 6: Employment projections for Texas Triangle, Southern Florida, and Gulf Coast Megaregions.
(Source: RPA)

4.3 Texas Triangle and Gulf Coast Megaregions

The Gulf Coast Megaregion experienced twelve hurricanes that were Category 1 or above when they made land contact between 2000 and 2017.[93] Of those 12 hurricanes, six were Category 1, one was Category 2, four were Category 3, and one was Category 4. The Gulf Coast Megaregion experienced a hurricane event 12 out of 17 years. The first seven hurricane events occurred in consecutive years, with four hurricanes occurring during the 2005 season, and three of the four making contact with land as Category 3 hurricanes.[94] Four hurricanes made landfall in the Gulf Coast Megaregion: Katrina (Category 3), Rita (Category 3), Dennis (Category 3), and Cindy (Category 1).

In 2005, Hurricanes Dennis and Cindy made landfall along the Gulf Coast Megaregion uncharacteristically early in the hurricane season. Hurricane Cindy landed as a Category 1 hurricane on the southeastern Louisiana coast, with one direct death and causing about $320 million in damages **(Figure 7)**.[95] Hurricane Dennis made landfall on the northwestern coast of Florida, resulting in 3 direct and 12 indirect deaths, and $2.5 billion in damages.[96] In August 2005, Hurricane Katrina depressed from a Category 5 hurricane to a Category 3 right before making landfall on the southern coast of Louisiana, centered in the greater New Orleans region. The devastating impacts of Katrina have made it one of the deadliest hurricanes in U.S. history, as well as the costliest. Katrina caused 1,500 direct deaths, and 1,833 indirect deaths. Thousands of people were displaced and relocated to other cities in the U.S. Katrina's impacts reached along the entire Gulf coast, extending as far as Alabama and Florida.[97]

In that same timeframe, the Texas Triangle Megaregion saw the landfall of two hurricanes: Hurricane Rita in 2005 and Hurricane Ike in 2008. Because of the geographic overlap between megaregions, Hurricane Rita counts for making landfall in both megaregions. In September 2005,

[93] (Office for Coastal Management, n.d.)
[94] (Office for Coastal Management, n.d.)
[95] (Stewart, 2006)
[96] (Beven, 2005)
[97] (Knabb, Rhome, & Brown, 2005)

Hurricane Rita made landfall as a Category 3 hurricane on the eastern edge of the Texas Triangle along the Texas/Louisiana border. The approach of Hurricane Rita caused one of the largest evacuations in U.S. history. Unfortunately, seven casualties were directly related to the storm, with an estimated 55 indirect deaths.[98] The cost of Hurricane Rita is estimated at $12 billion.[99]

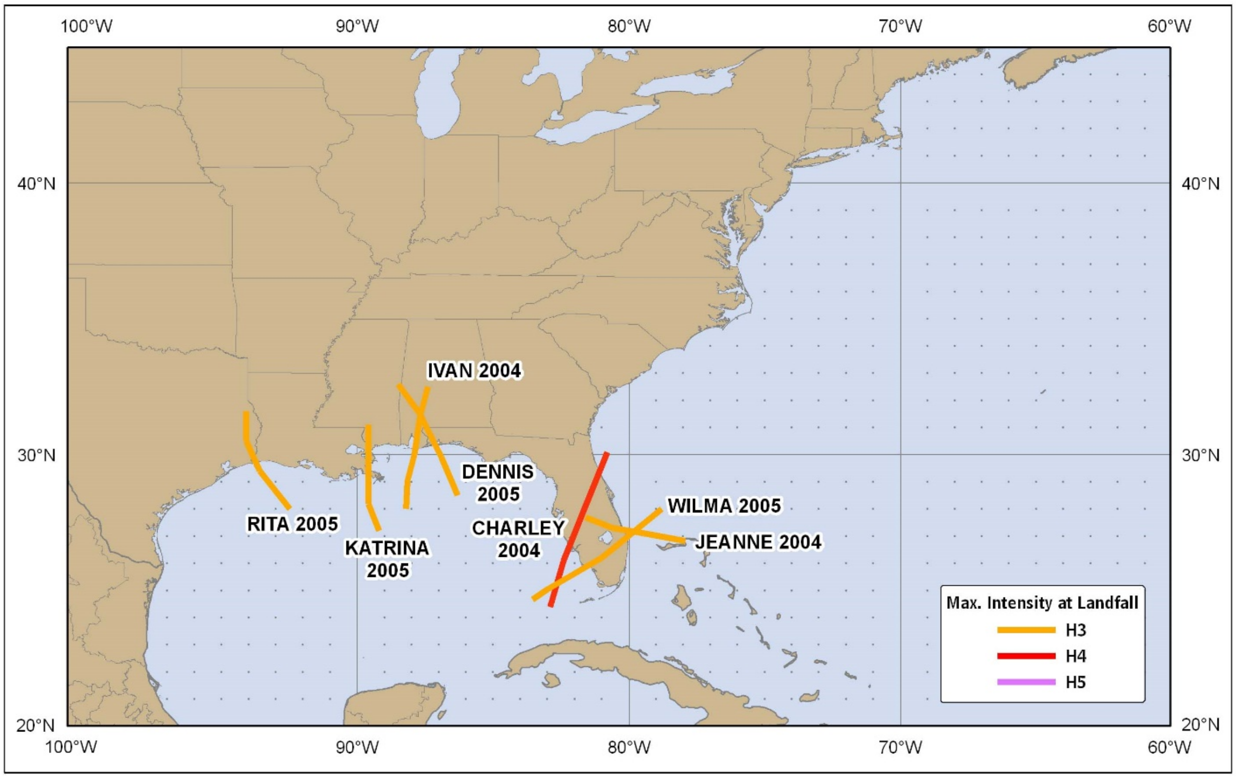

Figure 7: Hurricanes Category 3–5 in the 2005 hurricane season.
Map downloaded from National Hurricane Center and Central Pacific Hurricane Center.[100]

Tables 5 through 7 indicate the hurricanes that made landfall in the Texas Triangle or Gulf Coast Megaregions between 2001 and 2018.

[98] (Mayfield, 2006)
[99] (Mayfield, 2006)
[100] (National Hurricane Center, n.d.)

Table 5: Number of hurricanes to make landfall in Gulf Coast Megaregion 2000–2017.

Number of hurricanes by severity at land contact between 2000 and 2017	
Category 1	6
Category 2	2
Category 3	4
Category 4	1

Table 6: Specific hurricane events in Gulf Coast Megaregion by year and intensity.

Year	Name	Category at landfall
2002	Lili	H1
2003	Claudette	H1
2004	Ivan	H3
2005	Katrina	H3
2005	Rita	H3
2005	Dennis	H3
2005	Cindy	H1
2007	Humberto	H1
2008	Gustav	H2
2008	Ike	H2
2012	Isaac	H1
2017	Nate	H1
2017	Harvey[101]	H4

Table 7: Hurricanes in the Texas Triangle 2001–2017.

Year	Name	Category at landfall
2005	Rita	H3
2008	Ike	H2

[101] In 2018, Hurricane Harvey made landfall in Corpus Christi and Victoria, as a Category 4 hurricane. After making landfall, Harvey became a tropical storm, and it moved inland and slightly southeast of San Antonio (with its center never having moved more than sixty nautical miles offshore of the Texas coast), then tracked back out to the Gulf of Mexico over Matagorda Bay east of Port O'Connor , and then returned back to land on the Gulf Coast just west of Calcasieu Lake in Cameron Parish, Louisiana. Hurricane Harvey is known for the billions of dollars of damage done to the Houston metropolitan area; the damage was a result of continuous high amounts of rain that the city was not able to drain. In some areas, Texas counties received as much as 60 inches of rain.[101] The devastating effects of Hurricane Harvey were felt throughout south central and central Texas. For the purposes of this report, Hurricane Harvey is categorized as occurring in the Gulf Coast Megaregion and for its land contact as a Category 4 hurricane. In the future, when historic data is available, this report should be updated to examine the effect of Hurricane Harvey on population, employment, and personal income.

While Ike (2008) made landfall directly with the Houston metropolitan area, the analysis focuses on the 2005 hurricane season because it would be impossible to separate the effects of Ike on the two indicators from the effects of the 2008 economic recession. The sections below investigate how counties in both megaregions were impacted in terms of population and total employment and analyze the length of time required to return to pre-disaster levels.

The findings below provide context for RPA population and employment projections out to 2025 **Figures 8 and 9**) and are followed by actual population and employment numbers and changes in personal income between 2001 and 2017 **(Figures 10–12)**.

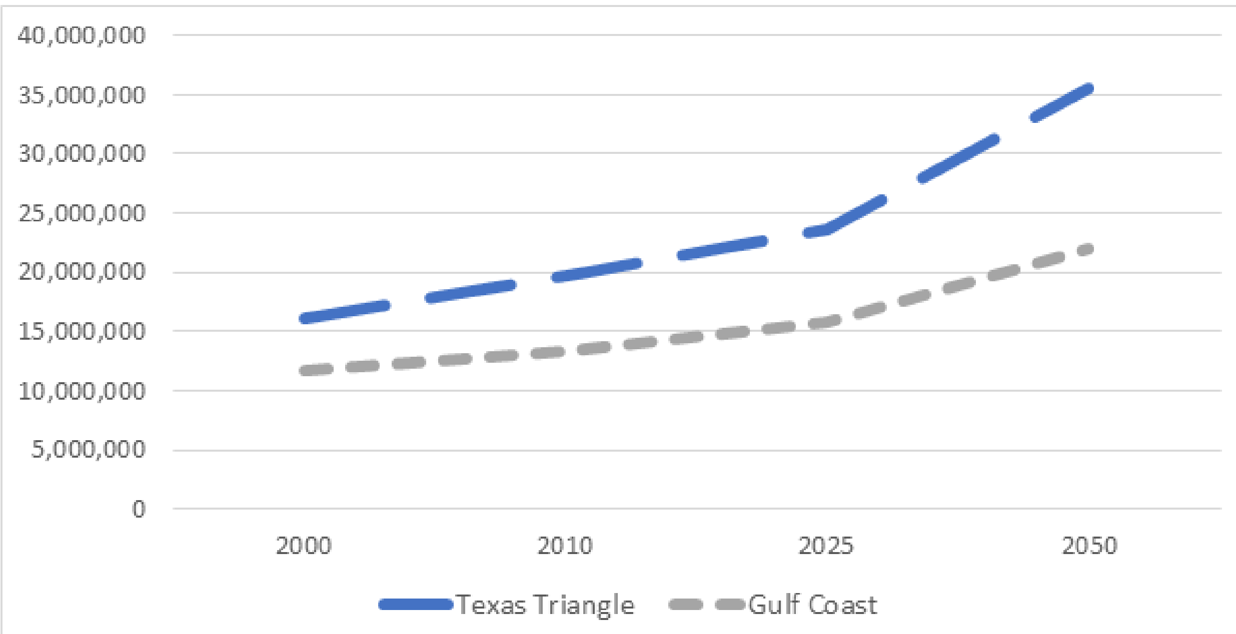

Figure 8: RPA population projections for Texas Triangle and Gulf Coast Megaregions.

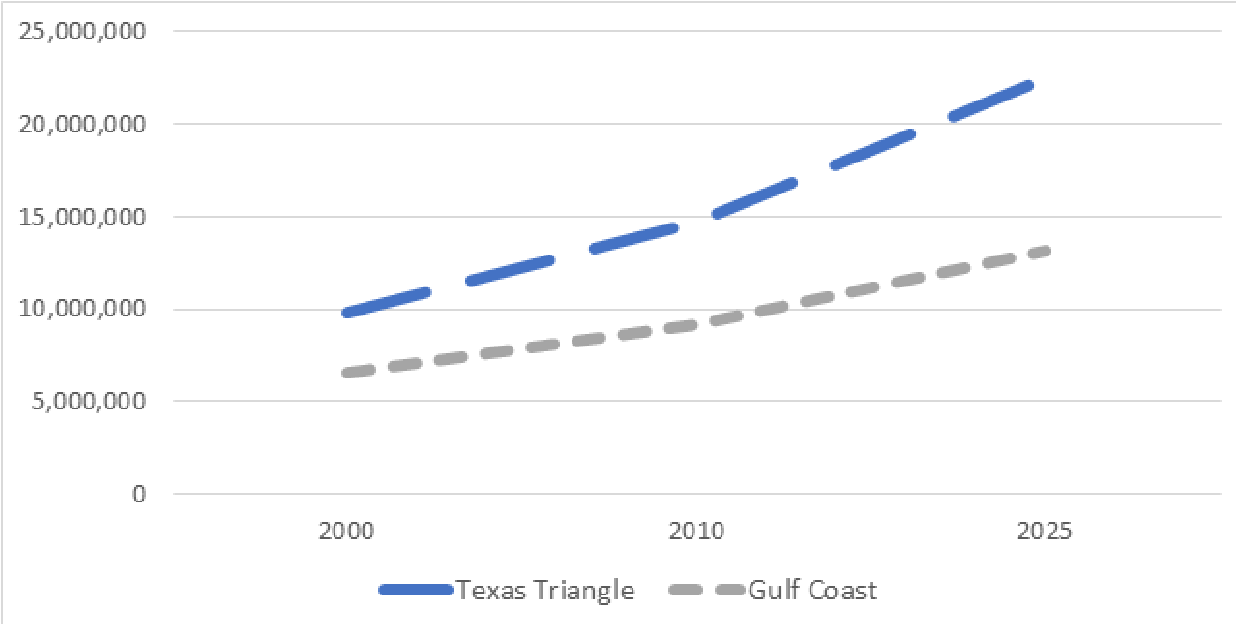

Figure 9: RPA employment projections for Texas Triangle and Gulf Coast Megaregions.

RPA population and employment projections predict steady growth in both megaregions for both categories. The predictions suggest that the Texas Triangle would grow at a faster rate than the Gulf Coast in terms of population, particularly after 2025. Overall, steady growth is expected in both megaregions. It is important to note that predictions for future population and employment are largely based on historical growth, limiting the ability for prediction models to consider system shocks such as natural disasters. The figures below offer insight into changes in population, employment, and personal income the timeframe of 2001–2017.

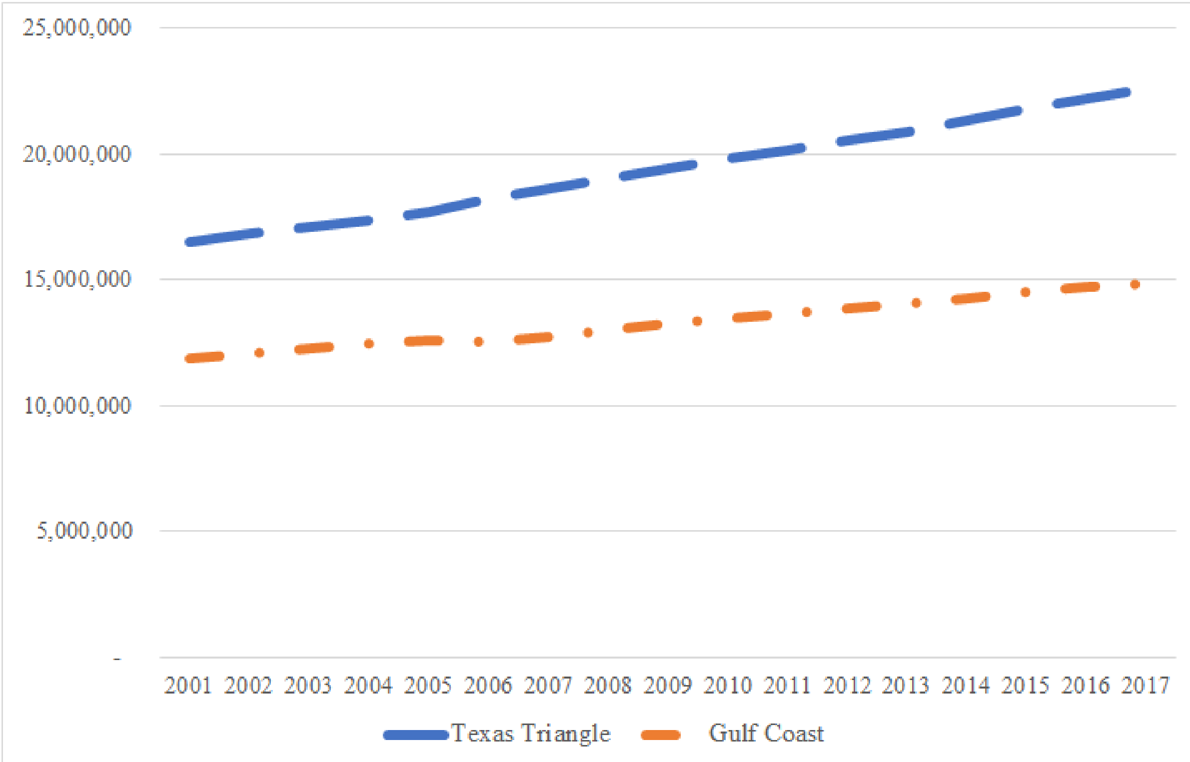

Figure 10: Gulf Coast and Texas Triangle: population change, 2001–2017.

Between 2005 and 2006, the Gulf Coast Megaregion experienced a 0.7% decrease in population at 85,944 people. Figure 8 illustrates a noticeable dip in population, but pre-Katrina population levels are recovered by 2017. No noticeable drop in total employment or personal income occurred between 2005 and 2006. Figures 9 and 10 illustrate that growth was steady in both indicators until the economic recession in 2008. The megaregional impact of the 2005 hurricane season appears minor at this scale, but 18 counties within the Gulf Coast Megaregion lost population. This is explored in more detail in subsequent sections.

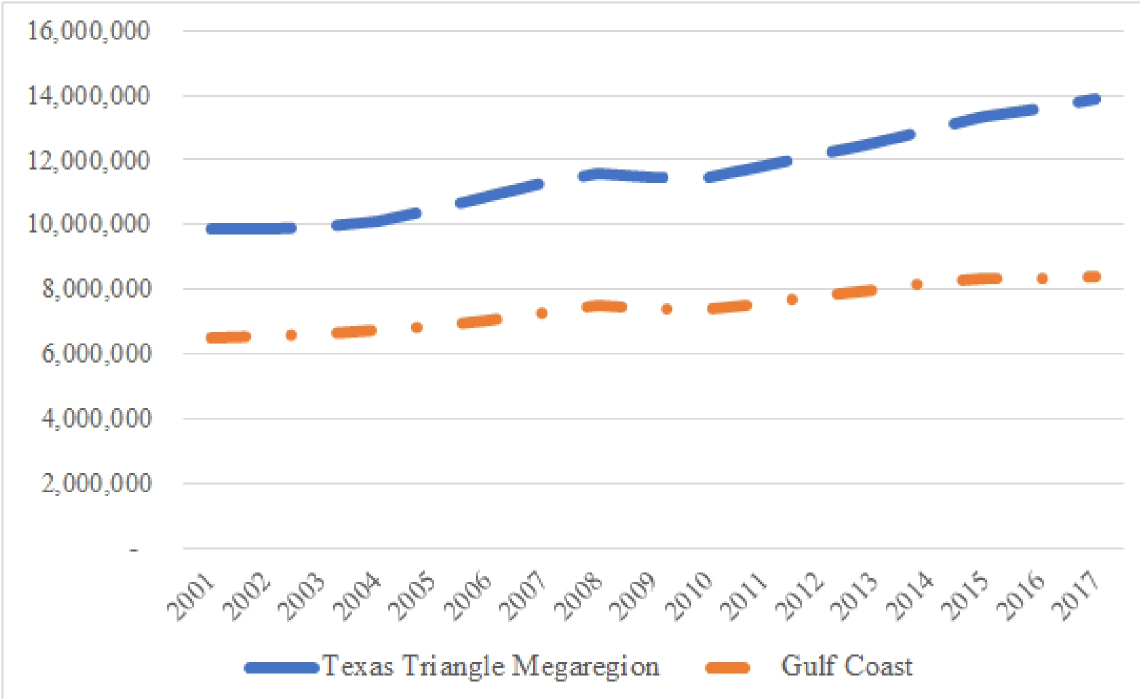

Figure 11: Change in total employment for Gulf Coast and Texas Triangle Megaregions from 2001 to 2017.

Between 2005 and 2006, the Gulf Coast Megaregion experienced a 2.8% increase of total employment with 191,399 added jobs. The Texas Triangle Megaregion gained 414,331 total jobs, at about a 4% increase.

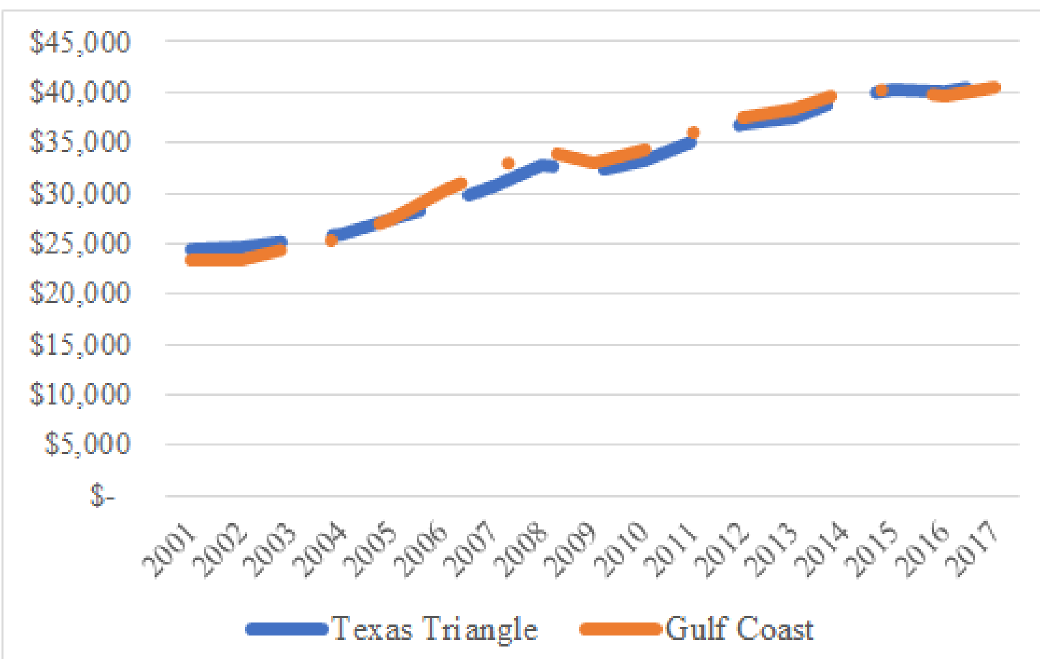

Figure 12: Change in personal income in Texas Triangle and Gulf Coast Megaregions.

Between 2005 and 2006, the Gulf Coast Megaregion experienced a 9.96% increase in personal income. The Texas Triangle Megaregion experienced a 6% increase in personal income.

The Texas Triangle did not experience a decrease in population, total employment, or personal income between 2005 and 2006. In fact, the megaregion gained 510,596 people at a 2.88% increase. Because the population increase in the Texas Triangle is substantially larger than the population loss experienced in the Gulf Coast Megaregion, it suggests that the population increase in Texas is not solely attributable to migration resulting from hurricane impacts. At this scale, it appears that the Texas Triangle was resilient to the impact of Hurricane Rita. More detailed analysis at the county level is explored in the next section and categorized by type of indicator.

4.3.1. Indicator: Population

Tables 8–9 and **Figures 16–17** provide specific county information for counties that lost population. The tables illustrate the percentage of population loss, and how long each county took to return to pre-disaster levels. Figures 16–17 illustrate the pace of this population change between 2005 and 2017. Population loss displayed in this information does not account for migration or deaths. **Figure 13** suggests that population loss in some counties could have resulted in population gain in adjacent counties. It is also possible that population loss or gain in central Texas counties is unrelated to impacts of the 2005 hurricane season. **Figures 14 and 15** illustrate that the counties that experienced the highest levels of population loss had not recovered pre-disaster population levels by 2017. This is supported by Tables 8–9 and Figures 16–17, which provide additional insight into the nuance of the level of change in each county that experienced population loss. The location of Falls County in central Texas (the only county to not recover initial levels of population loss) suggests that its population loss is not due to a lack of recovery or related to natural disaster events. This could be due to migration to adjacent metropolitan areas such as Austin or Waco.

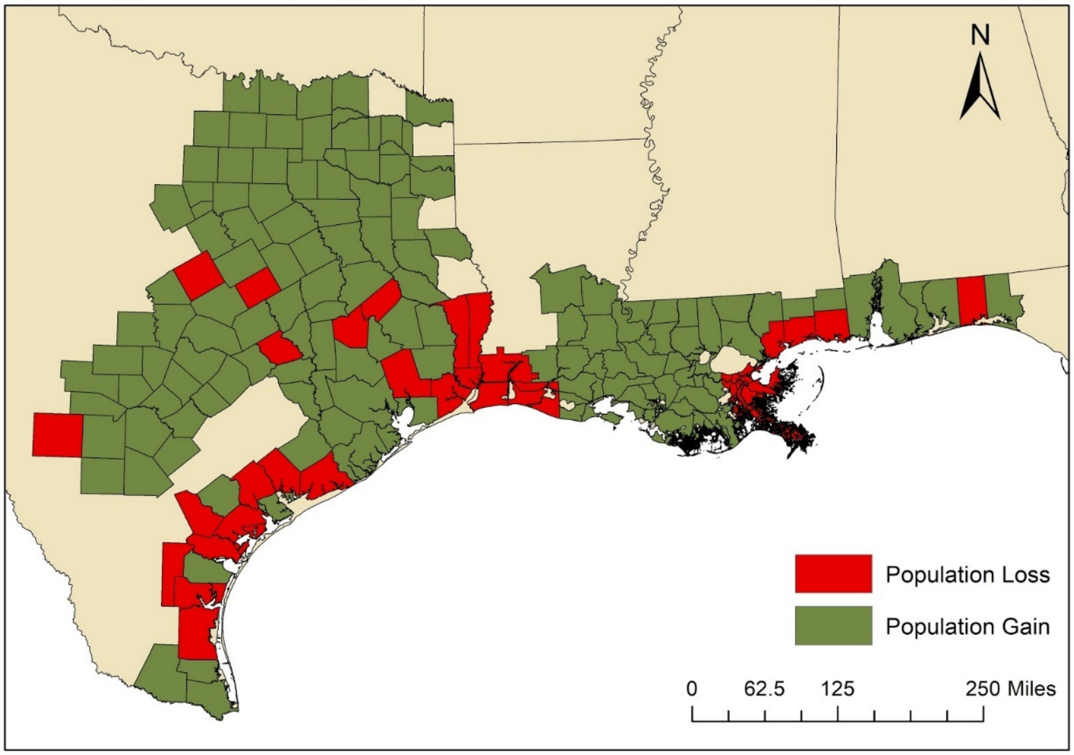

Figure 13: Texas Triangle and Gulf Coast Megaregions; counties that lost population between 2005 and 2006.

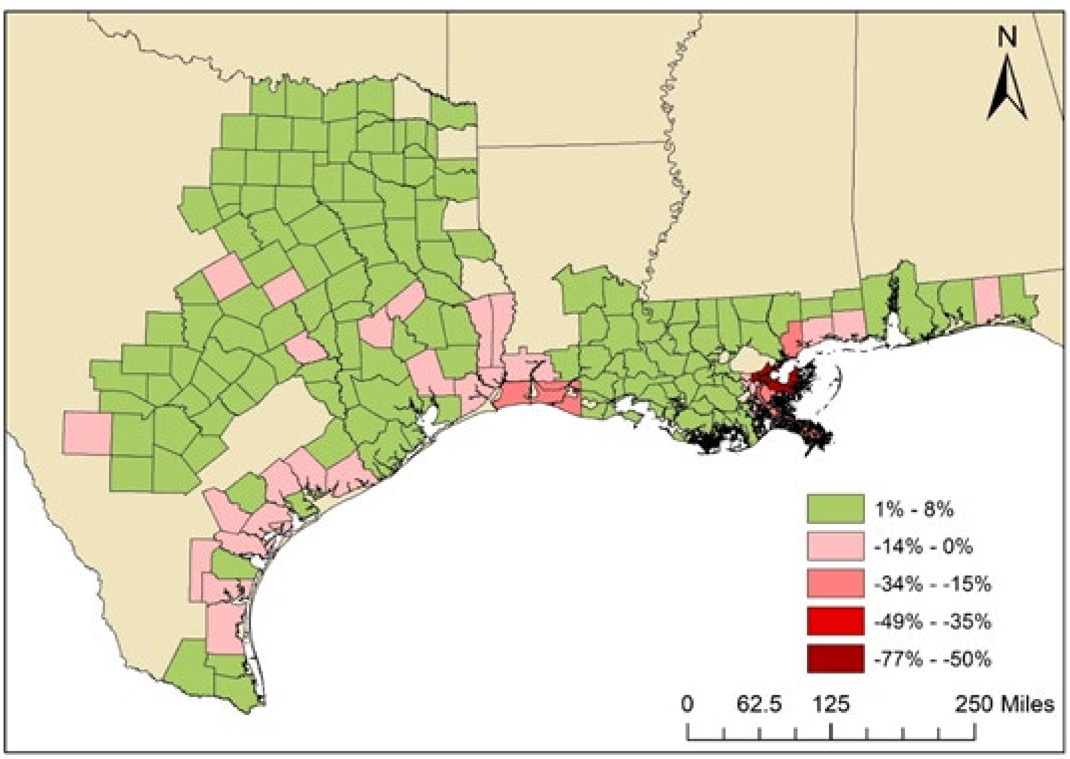

Figure 14: Texas Triangle and Gulf Coast Megaregions; degree of population loss by county between 2005 and 2006.

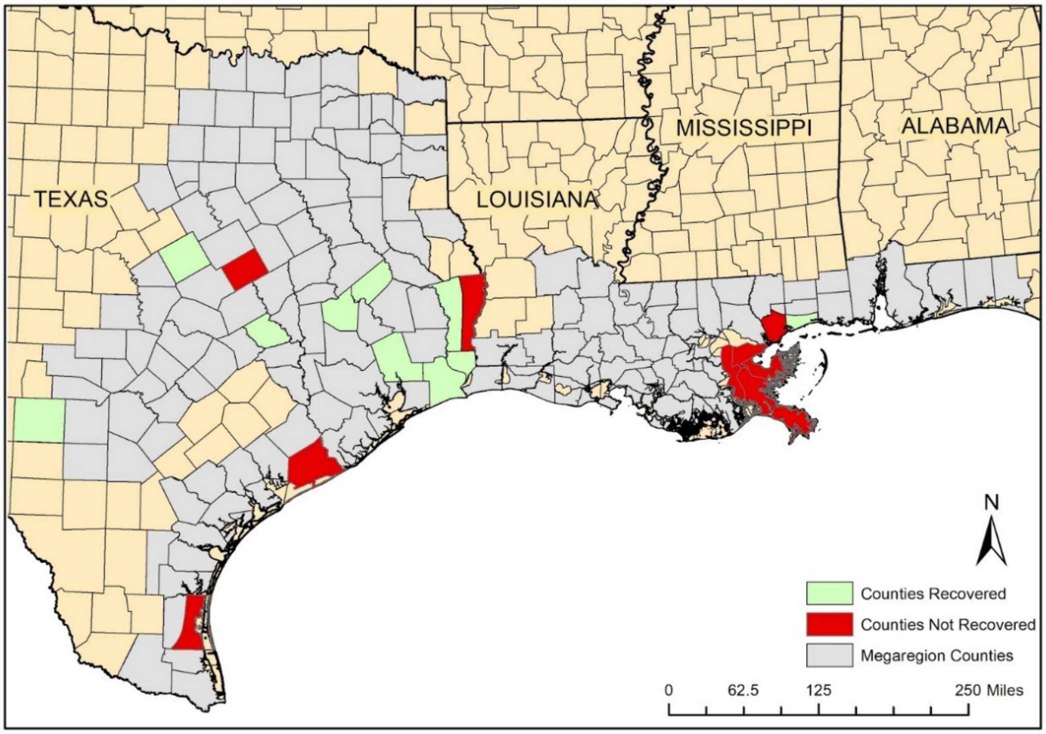

Figure 15: Texas Triangle and Gulf Coast Megaregions; recovery status by county that experienced loss in population, compared to pre-disaster levels.

Most counties or parishes in the Gulf Coast Megaregion that lost population between 2005 and 2006 had not recovered pre-disaster levels by 2017. While most hurricanes during the 2005 season made landfall along the Louisiana coast, it appears that impacts spread along the entire coast of Texas. It is possible that the population loss in these counties is due to other elements related to migration; however, that level of nuance is not able to be gleaned from this analysis. Louisiana parishes were dramatically impacted in terms of loss in population, and Hurricane Katrina appears to have had the longest lasting effects, visible by the southeastern tip of red in Louisiana in Figure 16.

Table 8: Counties in Texas Triangle Megaregion; population recovery.

County	Initial Population Loss 2005–2006	Number of Years to Regain Pre-event Population (2005–2017)	% of Pre-disaster Population Recovery by 2017
Burleson	-0.98%	4	104.92%
Coryell	-0.54%	1	103.17%
Falls	-0.25%	Not recovered	96.93%
Jasper	-2.00%	4	100.01%
Jefferson	-1.99%	3	102.17%
Liberty	-0.05%	1	112.59%
Matagorda	-1.06%	Not recovered	99.21%
Newton	-1.92%	Not recovered	95.40%
Orange	-2.22%	9	101.85%
Trinity	-0.13%	1	101.89%
Uvalde	-0.25%	4	102.90%
Walker	-0.13%	2	110.00%

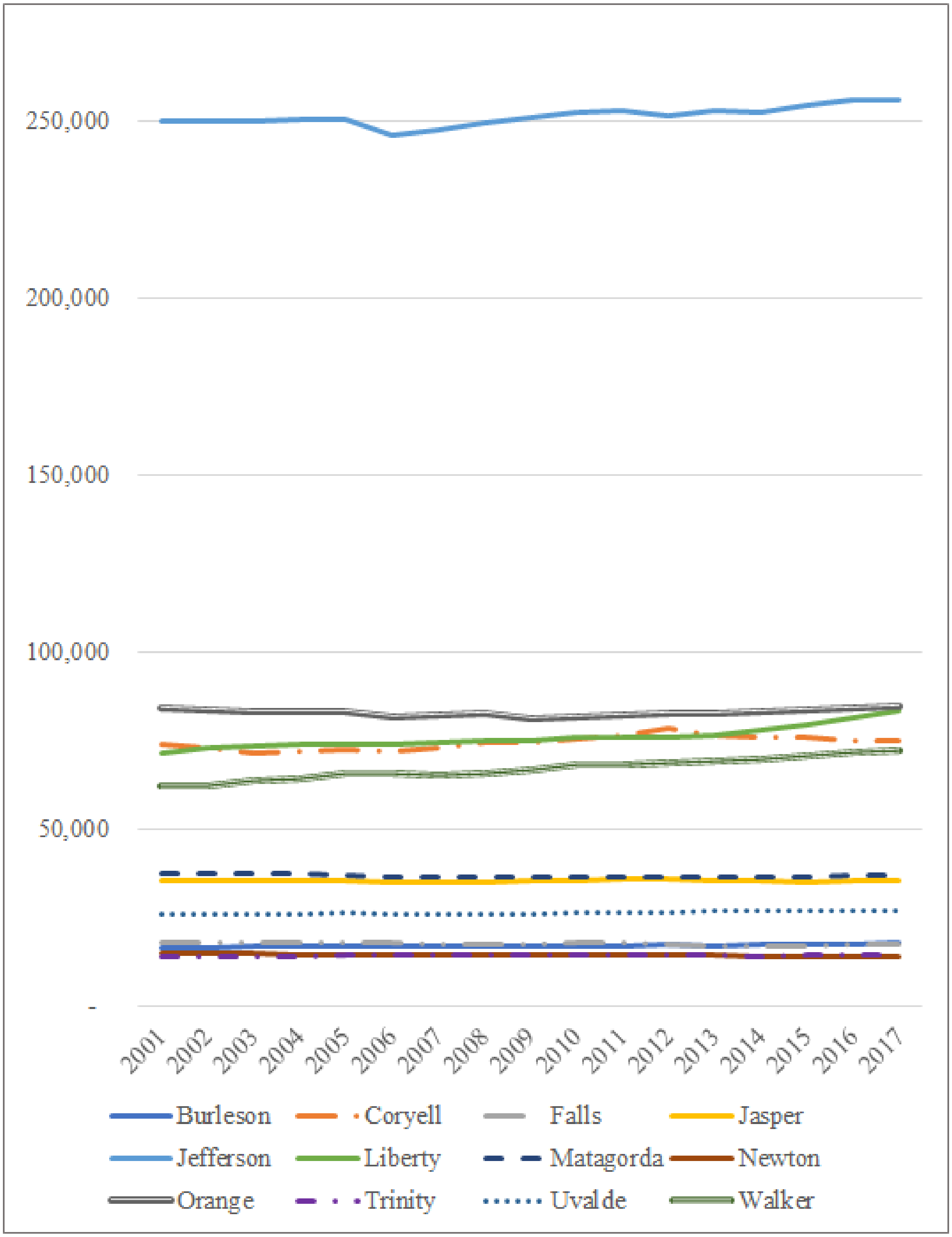

Figure 16: Population change of counties in Texas Triangle Megaregion that experienced population loss after 2005 hurricane season.

Table 9: Counties in Gulf Coast Megaregion; population recovery.

State	County	Initial Population Loss 2005–2006	Number of Years to Regain Pre-event Population (2005)	% of Pre-disaster Population Recovery by 2017
Mississippi	Hancock	-15.99%	Not recovered	99%
Mississippi	Harrison	-11.80%	9	104%
Louisiana	Jefferson	-6.63%	Not recovered	96%
Texas	Jefferson	-1.95%	4	102%
Texas	Kenedy	-6.78%	Not recovered	91%
Texas	Matagorda	-1.05%	Not recovered	99%
Texas	Orange	-2.17%	10	102%
Louisiana	Orleans	-53.43%	Not recovered	80%
Louisiana	Plaquemines	-24.46%	Not recovered	79%
Louisiana	St. Bernard	-76.77%	Not recovered	65%

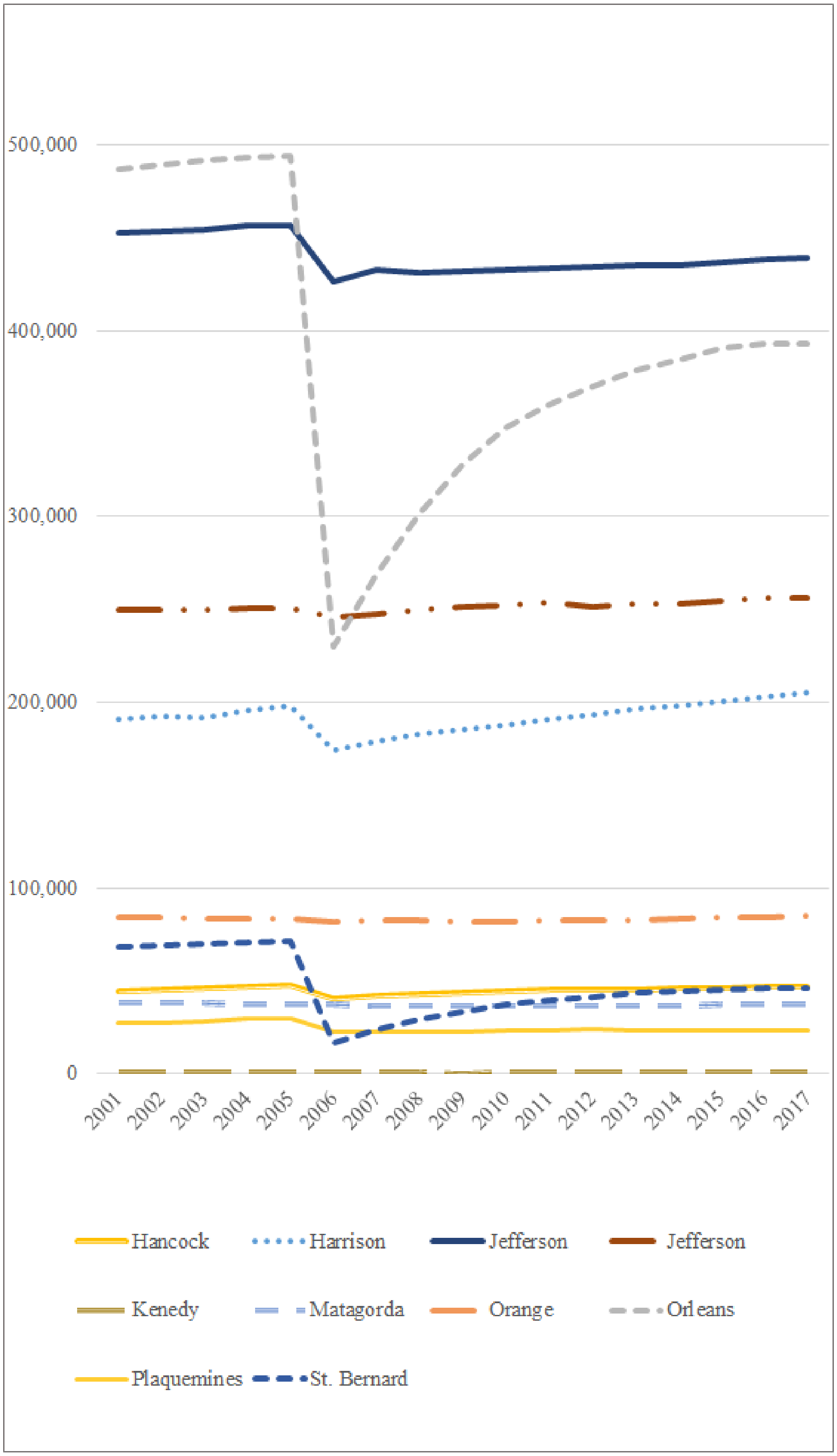

Figure 17: Population change of counties in Gulf Coast Megaregion that experienced population loss after 2005 Hurricane Season.

4.3.2. Indicator: Total Employment

Figures 18 through 20 illustrate employment trends.

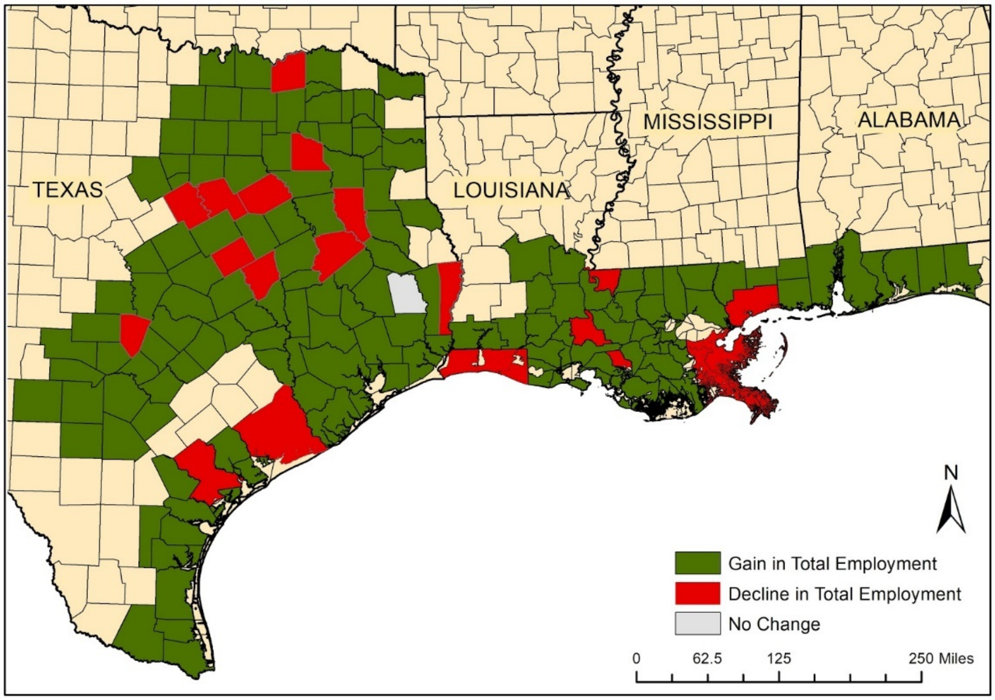

Figure 18: Counties that experienced a decrease in total employment 2005–2006.

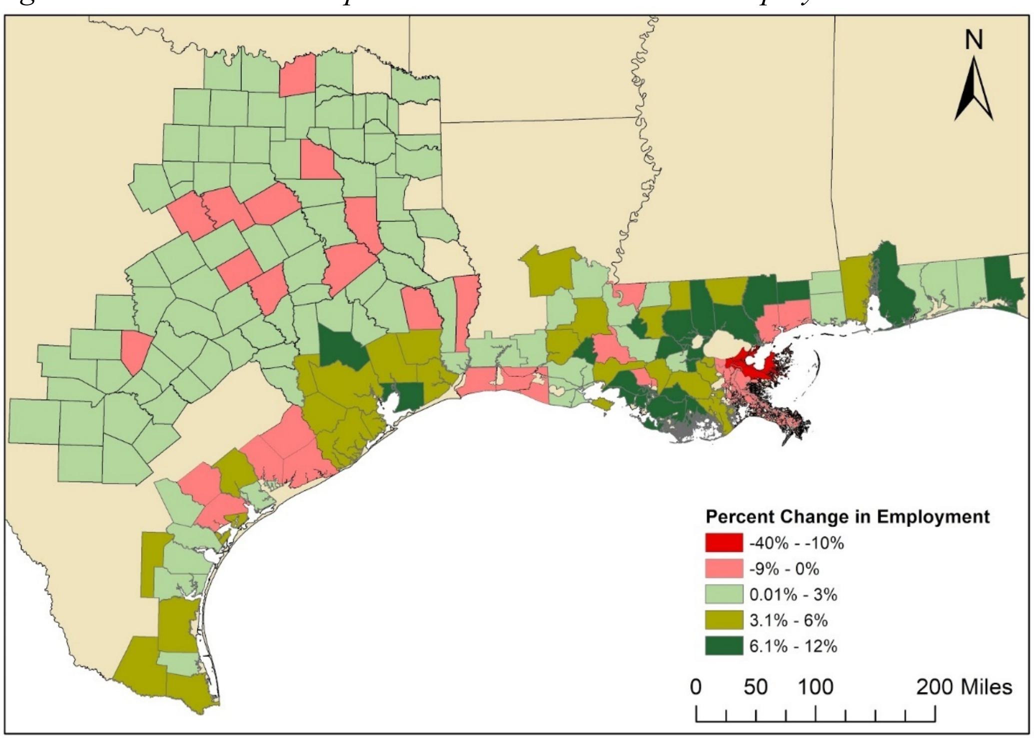

Figure 19: Percent change of total employment 2005–2006.

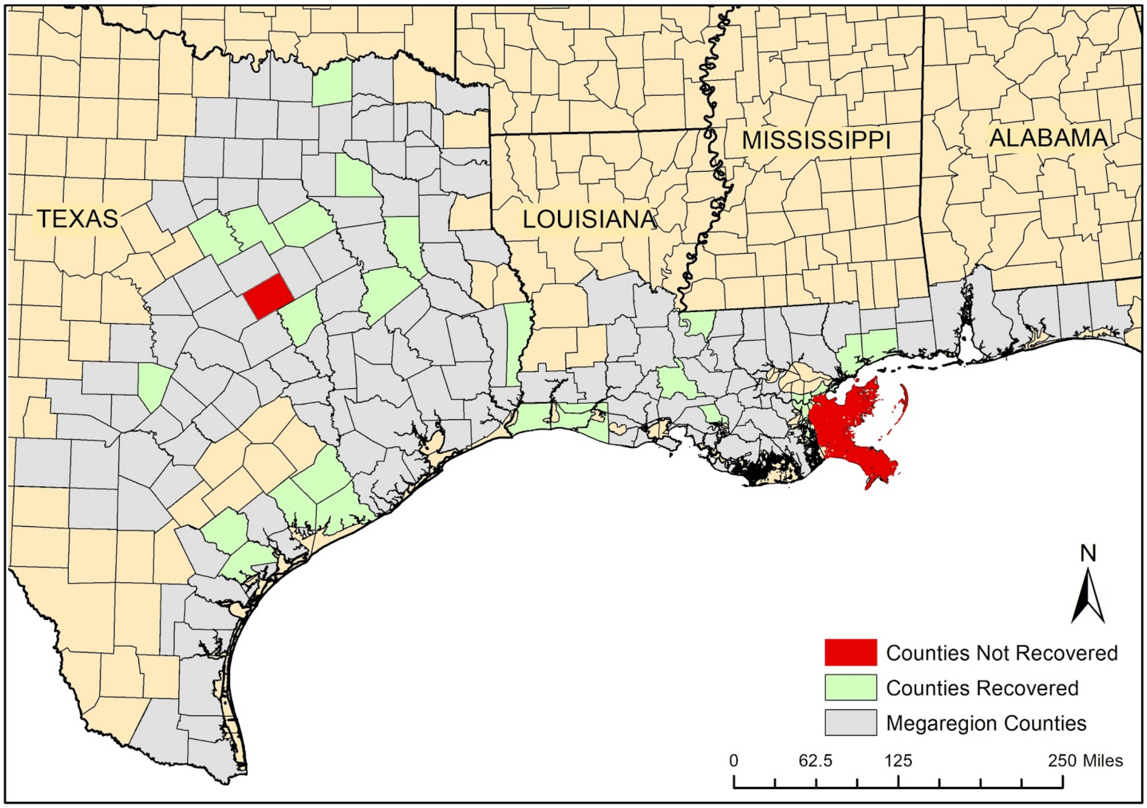

Figure 20: Recovery status in 2017 by county that experienced loss in total employment, compared to pre-disaster levels.

Of all counties and parishes where total employment levels were impacted, St. Bernard and Plaquemines parishes had not recovered initial levels of employment by 2017. This implies that many coastal industries and employment opportunities may have moved, or altered operations based on the damage from Hurricane Katrina. An analysis should be completed to evaluate the gross domestic product (GDP) of each parish, to determine whether the parishes have recovered in terms of ultimate output. Falls County in the Texas Triangle had been declining prior to the 2005 hurricane season and is considered irrelevant to the results of this specific analysis. A further analysis of the two parishes in Louisiana that have not recovered could include analyzing the types of industries and employment opportunities in 2017, and how those may have altered or changed since 2005. Findings of this type of analysis could suggest a mismatch between jobs available and skillsets of existing residents. It is possible that specific coastal industries will not come back to these parishes and have permanently relocated elsewhere. **Tables 10–11** and **Figures 21–22** include more information on the county-level analysis.

Table 10: Counties in Texas Triangle Megaregion; employment recovery.

County	Initial Employment Loss 2005–2006	Number of Years to Regain Pre-event Levels of Employment (2005–2017)	% of Pre-disaster Total Employment Recovery by 2017
Blanco	-0.13%	1	133%
Bosque	-2.26%	2	101%
Cherokee	-1.20%	1	103%
Falls	-2.62%	Not Recovered	97%
Fannin	-2.57%	2	108%
Hill	-0.15%	1	109%
Houston	-0.50%	1	110%
Matagorda	-0.75%	1	106%
Navarro	-0.48%	1	109%
Newton*[102]	-1.21%	1	77%*
Robertson	-0.54%	1	114%
Van Zandt	-0.26%	1	109%
Wharton	-0.23%	1	110%

[102] *Newtown county regained initial loss of employment by 2007. Employment declined again after 2008, suggesting that employment levels have not recovered from impacts of the economic recession. For the purposes of this analysis, it is considered as having recovered initial employment loss.

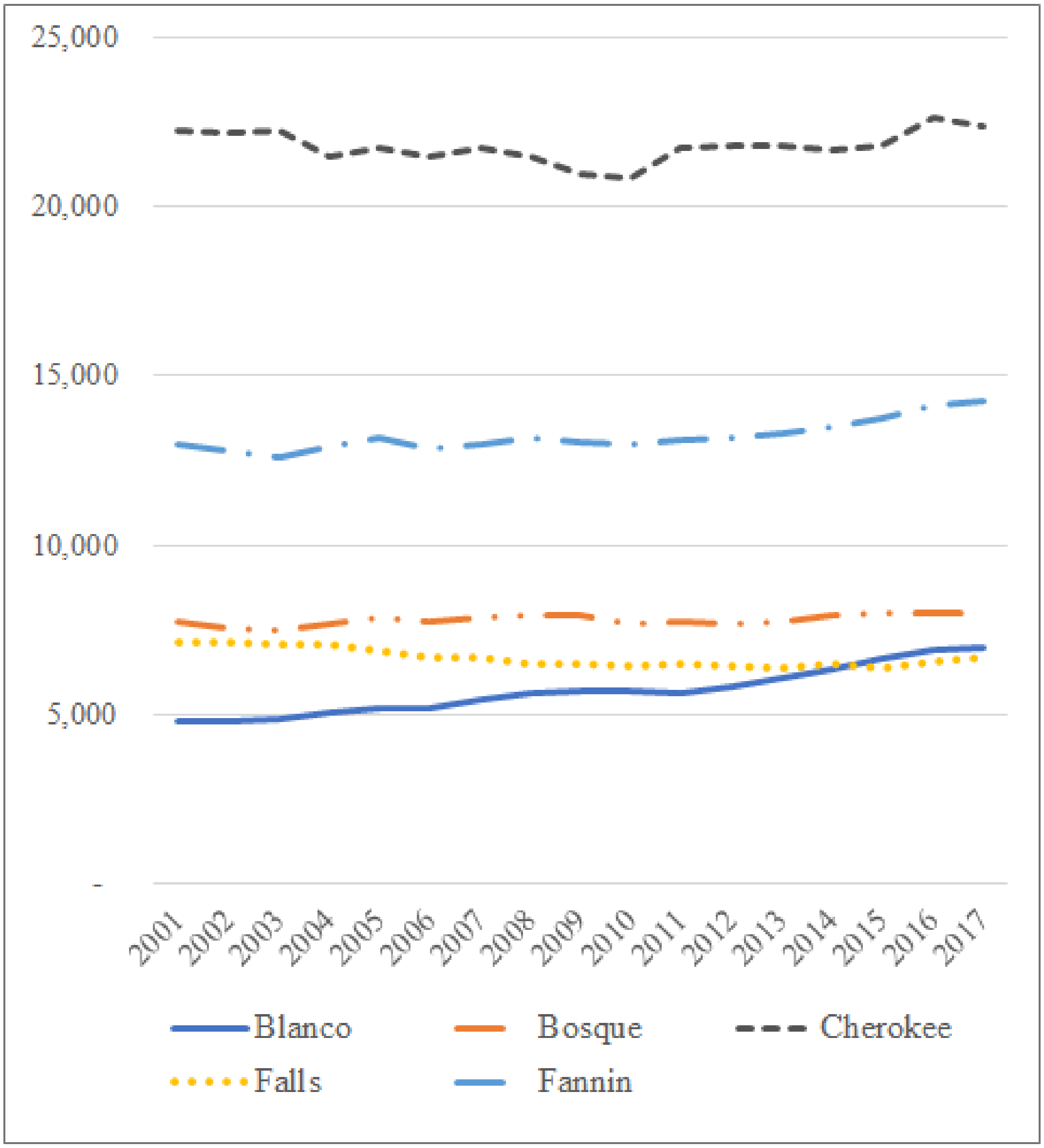

Figure 21: Total employment change by county in Texas Triangle that experienced more than 1% loss in total employment between 2005 and 2006.

Table 11: Gulf Coast Megaregion counties that experienced a decrease in total employment between 2005 and 2006.

County	State	Initial Employment Loss 2005–2006	Number of Years to Regain Pre-event Levels of Employment (2005–2017)	% of Pre-disaster Total Employment Recovery by 2017
Cameron	Louisiana	-6.15%	1	398%
Jefferson	Louisiana	-0.10%	1	110%
Orleans	Louisiana	-22.17%	7	110%
Plaquemines	Louisiana	-1.95%	Not Recovered	97%
St. Bernard	Louisiana	-39.93%	Not Recovered	99%
St. Martin	Louisiana	-0.35%	1	129%
West Feliciana	Louisiana	-2.76%	3	107%
Hancock	Mississippi	-1.55%	1	112%
Harrison	Mississippi	-4.25%	3	104%
Goliad	Texas	-0.47%	1	113%
Jackson	Texas	-0.92%	1	119%
Refugio	Texas	-0.53%	1	118%
Matagorda	Texas	-0.75%	1	106%
Wharton	Texas	-0.23%	1	110%

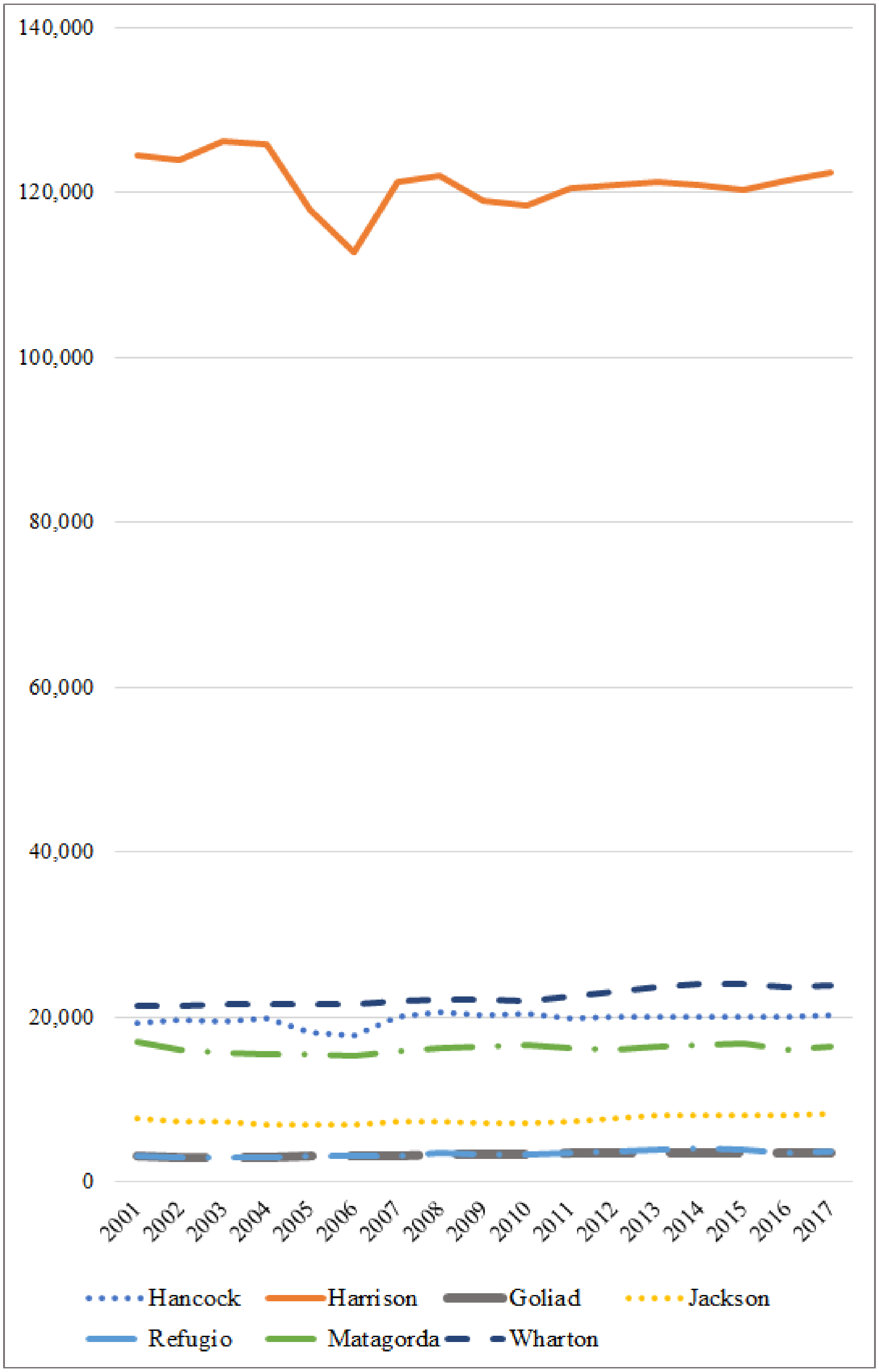

Figure 22: Total employment change by county in Gulf Coast Megaregion that experienced more than 1% loss in total employment between 2005 and 2006.

Out of all counties between the Texas Triangle and Gulf Coast Megaregions, by 2017 only three counties had not recovered from the loss of employment from 2005 to 2006.

4.4 Southern Florida Megaregion

Between 2001 and 2017, six hurricanes made landfall in the Southern Florida Megaregion: two Category 4 hurricanes, two Category 3 hurricanes, and one hurricane of both categories 1 and 2 (**Table 12**). This analysis focuses on the 2004 hurricane season, when three hurricanes made landfall in the Southern Florida Megaregion. At the megaregion level, the population increased from 2004 and 2005 by 402,168 people. Total employment increased by 12,334 people. **Figure 23** and **Figure 24** illustrate the change in each indicator from 2001 to 2017.

Table 12: Southern Florida Megaregion: hurricanes that made landfall between 2001 and 2017 by category.

Year	Name	Category at landfall
2004	Jeanne	H3
2004	Frances	H2
2004	Charley	H4
2005	Wilma	H3
2016	Hermine	H1
2017	Irma	H4

As noted, three different hurricanes made landfall in the Southern Florida Megaregion in the 2004 hurricane season. Hurricane Charley made landfall as a Category 4 hurricane on August 9, 2004 and is considered the sixth costliest hurricane to make landfall in mainland United States between 1900 and 2010.[103] Charley was responsible for 15 direct deaths and 25 indirect deaths, and cost approximately $15 billion.[104] Hurricane Frances made landfall as a Category 2 hurricane on August 25. Frances is directly responsible for seven deaths, and 43 indirect deaths. Estimates of costs of damage from this hurricane are $9.5 billion, making Frances the eight costliest U.S. hurricane to occur between 1900 and 2010.[105] Hurricane Jeanne made landfall in Florida in September as a Category 3 hurricane. The death toll in Haiti from this hurricane amounts to over

[103] (Blake, Landsea, & Gibney, 2011); (Pasch, Brown, & Blake, 2004)
[104] (Pasch et al., 2004)
[105] (Ii, 2014)

3,000 people. U.S. direct deaths are estimated to be about four people. The cost of U.S. damage is estimated to be $7.66 billion.[106]

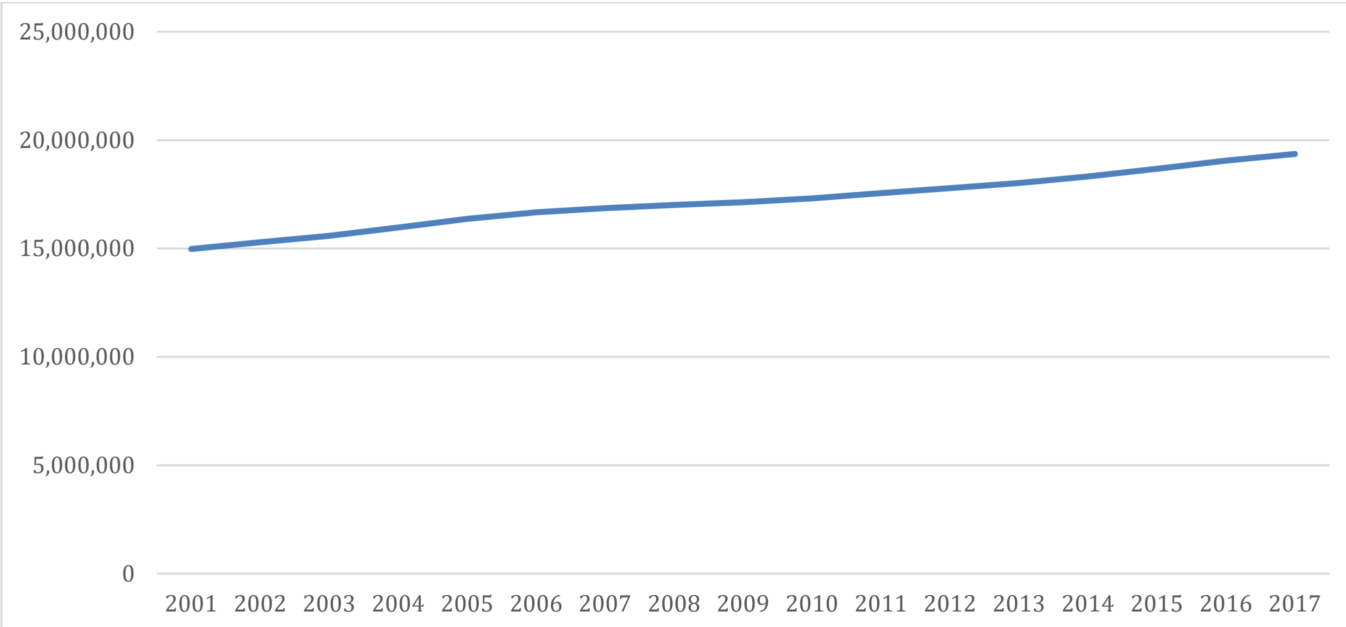

Figure 23: Southern Florida Megaregion, population change between 2001 and 2017.

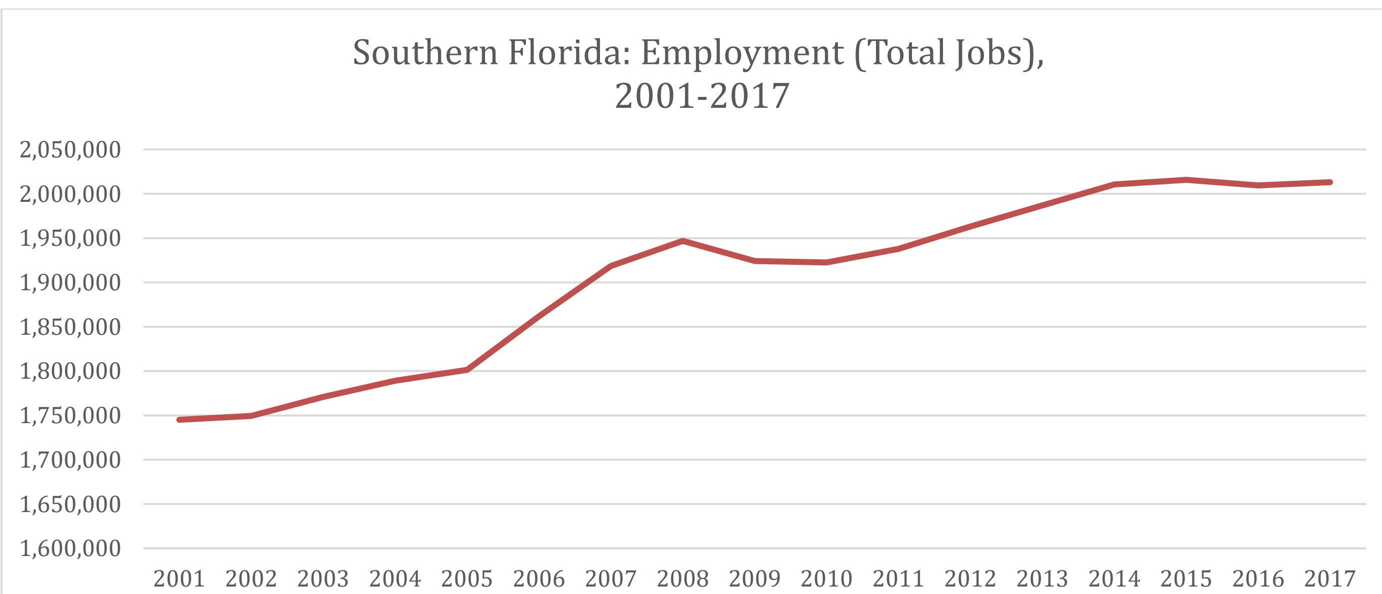

Figure 24: Southern Florida Megaregion, change in total employment between 2001 and 2017.

[106] (Lawrence & Cobb, 2005)

4.4.1. Indicator: Population

Figure 25 shows that some counties lost population after the 2004 hurricane season, with the highest degree of loss at -2%. Other counties gained up to an 11% increase in population between 2004 and 2005. By 2017, DeSoto and Charlotte counties had recovered pre-disaster population levels, and Monroe County had recovered about 99% of its initial population loss.

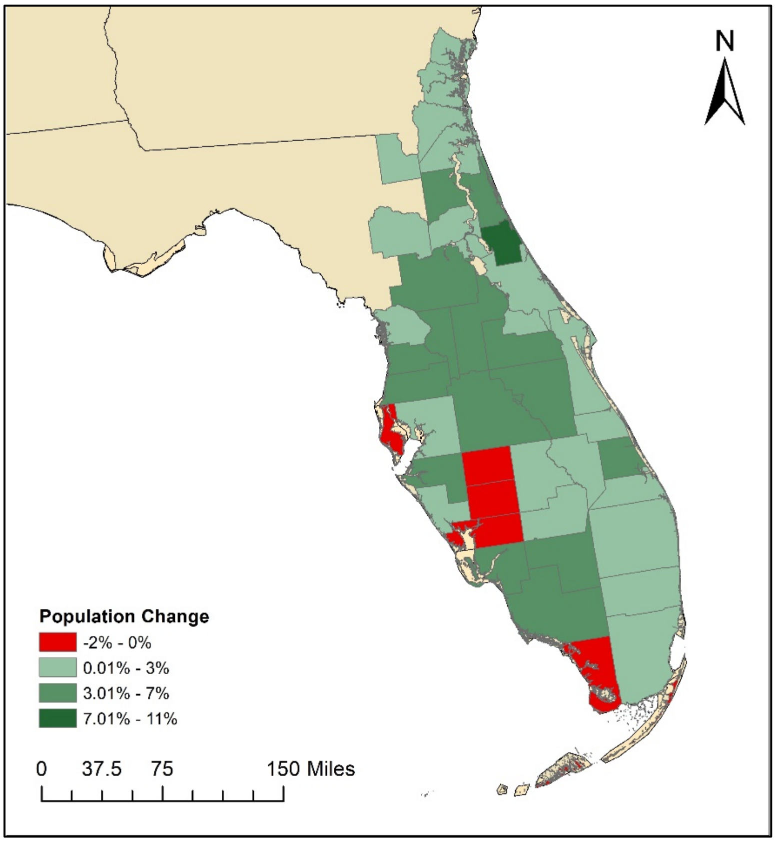

Figure 25: Southern Florida, degree of population change between 2004 and 2005.

Figure 26 and **Table 13** highlight the location of counties that recovered pre-disaster population levels, and the one that had not. Evaluating the numbers alone and trajectory of population growth for each of these three counties does not provide a clear explanation for why population levels may have recovered in one area and not another. It is also unclear how much population loss may be due to populations moving to adjacent counties. **Figure 27** shows the rate of population change from year to year between 2001 and 2017.

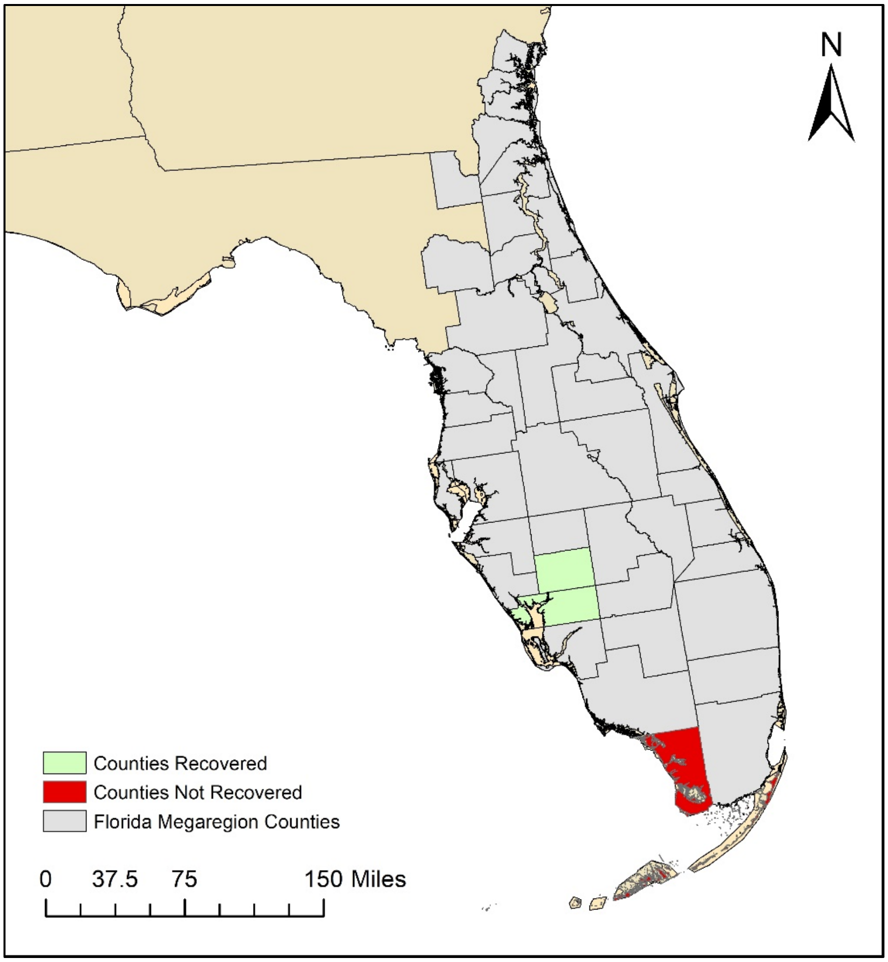

Figure 26: Southern Florida, population recovery status of countries by 2017.

Table 13: Recovery status of counties that lost population in Florida between 2004 and 2005.

County	Initial Population Loss 2004–2005	Number of Years to Regain Pre-event Population (2004–2017)	% of Pre-disaster Population Recovery by 2017
Charlotte	-1.58%	2	115%
DeSoto	-0.09%	1	109%
Monroe	-2.32%	Not recovered	99%

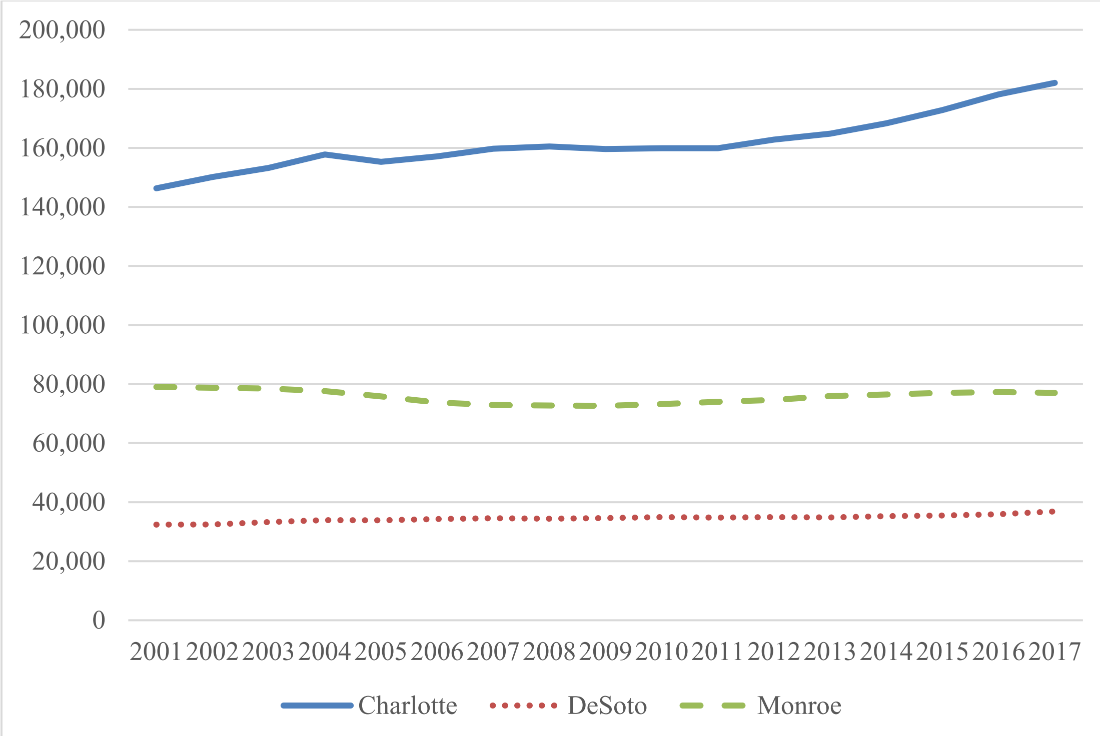

Figure 27: Southern Florida, population recovery by county between 2005 and 2017.

After a decline in population between 2004 and 2005, Charlotte County stayed on a steady pace of increasing the county's population. Levels rose more significantly between 2013 and 2017. DeSoto County experienced minimal change in levels of employment, remaining under 40,000 for all of the studied timeframe. Monroe County, however, appears to have had stable population levels until 2004, after which numbers declined and stagnated until about 2010, when population numbers began to almost recover to 2004 numbers.

4.4.2. Indicator: Employment

After the 2004 hurricane season, counties in the Southern Florida Megaregion suffered a decrease of up to 31.4% of total employment (**Figure 28**). These counties have some overlap with the counties that experienced population loss between 2004 and 2005, but the counties are not completely aligned. Additionally, seven more counties suffered a decrease in total employment, whereas three counties experienced a decrease in total population.

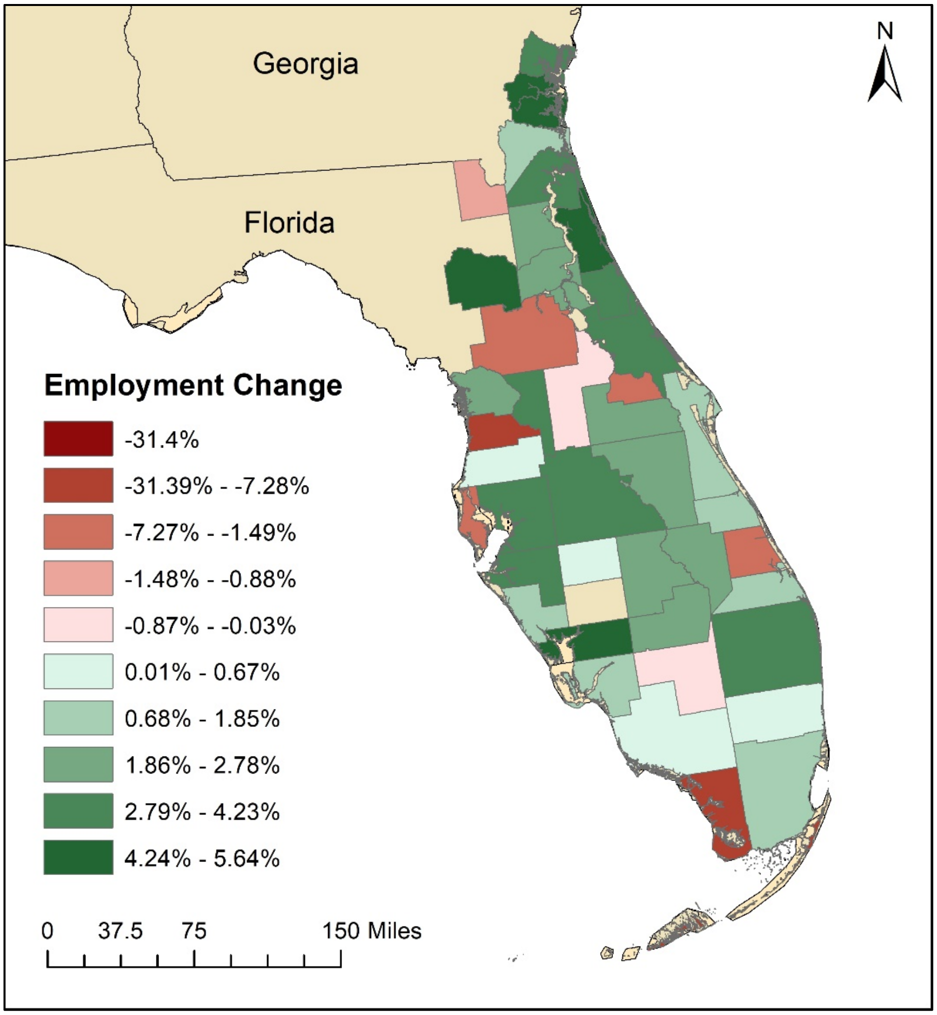

Figure 28: Degree of change in total employment by county between 2004 and 2005.

By 2017, eight of the ten counties recovered the initial decrease of total employment from the 2004 hurricane season. Three counties appear to still be recovering from the initial decrease in total employment. However, a closer analysis reveals that initial levels of decrease in total employment recovered, and the counties are experiencing a second drop in total employment levels. **Figure 29 and Table 14** identify the counties still recovering to pre-disaster employment levels and **Figure 30** depicts the annual change in total employment by county.

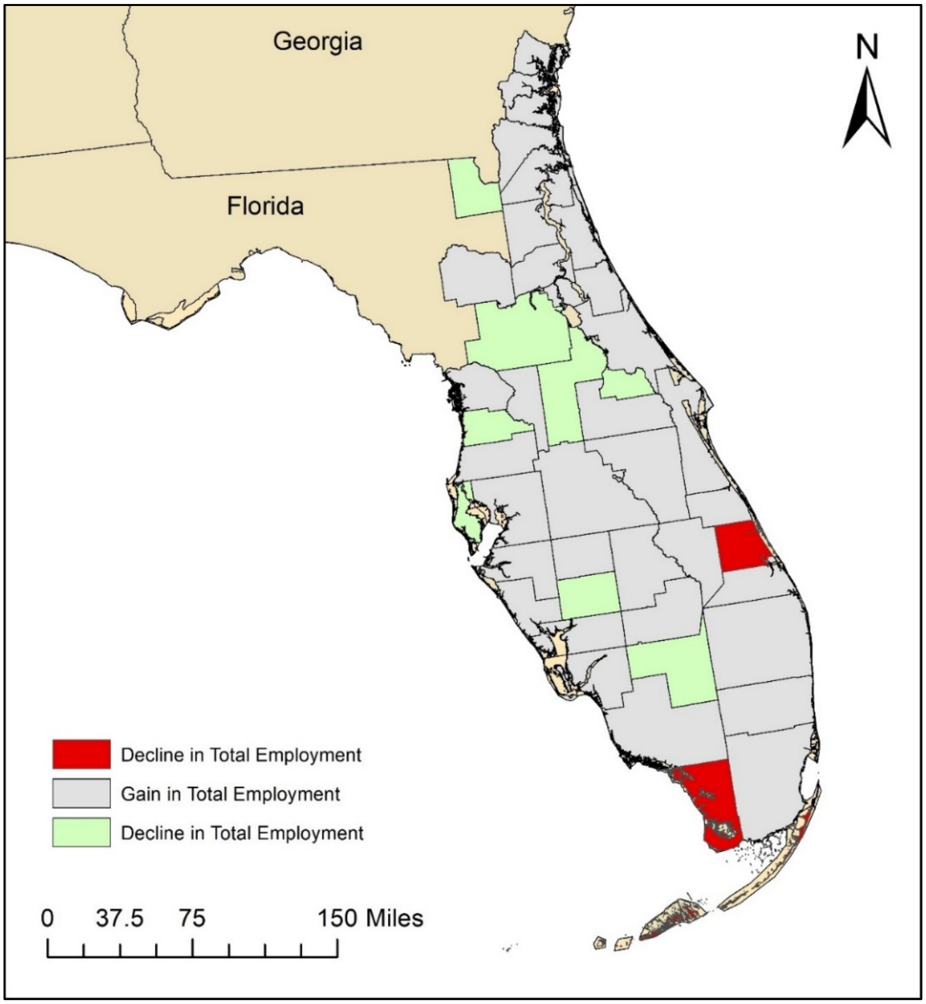

Figure 29: Recovery status of counties by 2017.

Table 14: Recovery status by county between 2005 and 2017. [107]

County	Initial Employment Loss 2005–2006	Number of Years to Regain Pre-event Employment (2004–2017)	% of Pre-disaster Employment Recovery by 2017
Baker*	-1.21%	1	99%
DeSoto*	-0.03%	1	97%
Hendry	-0.35%	2	106%
Hernando	-7.28%	11	102%
Lake*	-0.88%	2	97%
Marion	-1.92%	2	126%
Monroe	-31.40%	Not recovered	68%
Pinellas	-1.57%	1	142%
St. Lucie	-1.85%	Not recovered	95%
Seminole	-1.49%	1	109%

[107] * Indicates that employment recovered and then dipped back down.

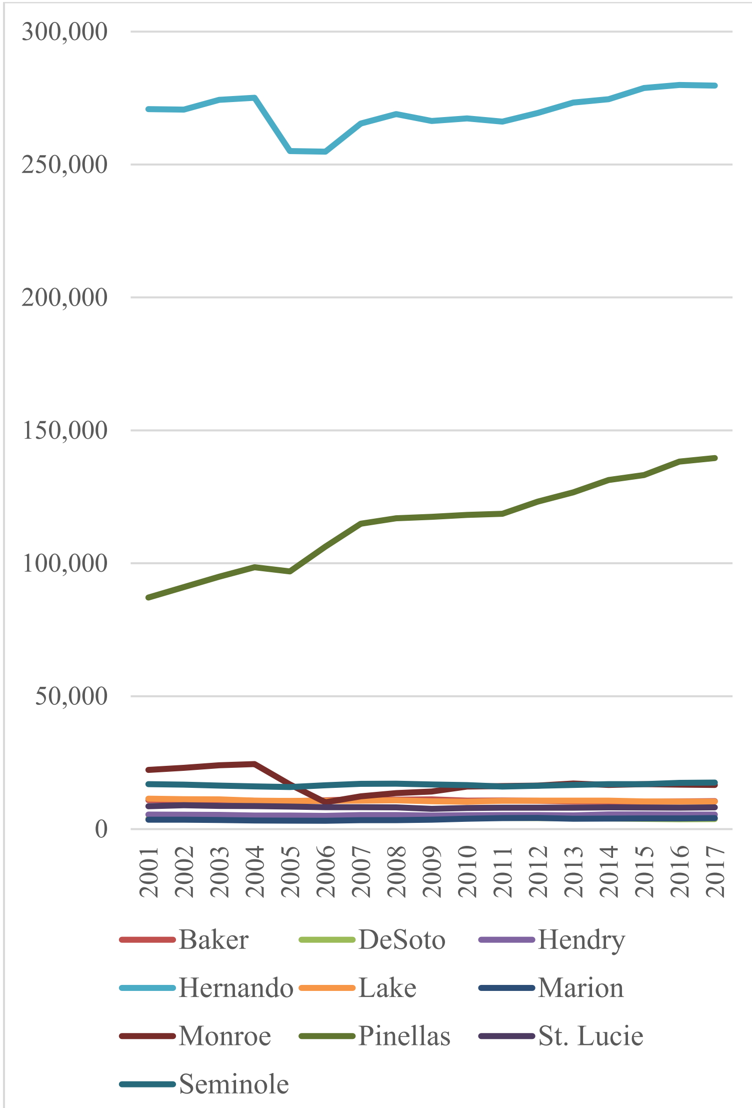

Figure 30: Annual change in total employment by county, 2001–2017.

Monroe and Hernando counties experienced the most dramatic decrease in total employment between 2004 and 2005, at a 31% and 7% decline, respectively. Hernando recovered the initial loss in employment after 11 years, and Monroe has recovered about 68% of pre-disaster employment levels. The individual characteristics and variables that facilitate improvement in some counties and not others are unknown. Future evaluations should take a deeper look at the county-level dynamics to understand how different factors are impacting the megaregional perspective addressed in this study.

4.5 Implications and Takeaways

While this research does not provide conclusive information about the level of resilience of the three megaregions, it applies existing methods used to measure resilience to a new geographic scale. At the megaregion scale, all three megaregions appear, on the surface, to be relatively resilient.

The Texas Triangle did not experience population decline after 2005 at the megaregion scale. The megaregional population increased by 8% between 2005 and 2006, and grew 28% from 2005 to 2017. In terms of employment, the megaregion saw an increase of 3.8% between 2005 and 2006. Between 2005 and 2008, total employment increased by 11%, and saw an overall increase of 33% between 2005 and 2017.

The Gulf Coast Megaregion experienced a decrease of 0.68% decrease in population between 2005 and 2006 at the megaregion scale. Between 2005 and 2008, the megaregional population increased by 3%, regaining pre-disaster population levels by 2007. Between 2005 and 2017, the population had increased from 2005 levels by 18%. Employment increased by 2.8% at the megaregion scale from 2005 to 2006. Between 2005 and 2008, employment increased by 9%, and increased by 23% over the course of 2005 to 2017.

The Southern Florida Megaregion experienced a 2.5% increase in population between 2004 and 2005. Between 2005 and 2008, the megaregion experienced a 6.5% increase in population, and a 21.3% increase between 2004 and 2017. Employment in the megaregion followed a similar pattern, with a modest increase of 0.7% between 2004 to 2005, a larger increase of 8.8% between 2005 and 2008, and a 12.5% increase between 2004 and 2017.

One limitation in this study is the type of data available at the county level for the specific years desired. It would be valuable for future research to focus on the impact of hurricanes specifically on transport infrastructure. Flooded or damaged roadways can impede necessary aid from reaching hospitals or displaced residents in need. Additionally, the number of days that airports or seaports are shut down after a storm event can have dramatic economic ramifications to a megaregion. A next step for this research could also include analyzing demographic changes pre-and post- event, as well as impacts to specific industries. The lack of continuous data within transport industries across counties is what led the research team to evaluate population and employment indicators.

The following section includes three-pager resilience profiles for all 11 U.S. megaregions.

Chapter 5. Megaregion Resilience Profiles

This section consists of three-page megaregional resilience profiles, listed in alphabetical order of megaregion names. The profile pages were developed to provide a tool for future megaregional resilience research. The information presented on each page can provide a foundational reference and starting point to understand the types of disasters and climate threats that impact megaregions in different geographic areas of the U.S.; these profiles outline some of the efforts conducted to date, including the resilience improvements that transportation agencies have made with federal assistance. We looked for a tool like this when we began to investigate a more nuanced approach to the role of transportation in natural disasters and could not find one. Therefore, we created a resource that we hope will help to jumpstart future research by hosting several key pieces of information in one place. As our research focuses on transportation resilience, the reference sheets also focus on transportation agencies and on pinpointing the effects of different disaster events on transportation assets.

The set of megaregional resilience profile pages included in the section below were created from multiple sources. The RPA website was used for geospatial data for each megaregion, and as the source of population data and the list of principal cities of each megaregion. Information regarding transportation organizations in each megaregion was determined by the researchers through GIS. The most common natural threat information was collected from the U.S. Natural Hazards Index, created by Columbia University's National Center for Disaster Preparedness.[108] The U.S. Natural Hazards Index online portal identifies the level of risk of different natural disasters by county in the United States; the researchers surveyed the levels of risk and type by county in each megaregion and manually summarized the risks of highest intensity by megaregion. Pilot program information is referenced and used from the FHWA Sustainable Division website, which reports on climate adaptation case studies. An example of recent natural disaster events and effects were included to provide insight into the specific context of each individual megaregion.

A map is included on each profile page to outline the megaregion, its various counties, and its MPOs. Note that the size of cities is determined by city limits, and not by greater metropolitan

[108] (Columbia University, 2019)

statistical area. The maps provide a visual reference for the geographic context of challenges each megaregion faces in terms of planning the transport system, given the natural disasters likely to occur in that area. Understanding the variety of challenges that different megaregions experience and efforts made to date toward climate adaptation and mitigation work can catalyze future innovations at lower levels of government, reducing reliance on federal pilot programs.

5.1 Arizona Sun Corridor

Arizona's desert climate is subject to intense heat and drought conditions. Climate change has increased the number of summer and fall temperature days, resulting in longer, more intense, and more frequent periods of drought. Droughts make conditions more susceptible to wildfire outbreaks, increasing potential for hazardous events. These conditions also impact the water supply, human health conditions, agricultural production, and other ecosystems.[109]

In June 2013, after a long summer drought and warning from the National Weather Service of an excessive heat watch in Arizona, lightning sparked a fire in Yarnell, Arizona.[110] The conditions of extreme drought and heat combined with an increased fuel load created a situation that lent itself to fire. The Yarnell fire spread and grew rapidly, growing to a size of 300 to 500 acres two days later. Strong and shifting winds unexpectedly changed the course of the fire, making it difficult to combat and protect against. Tragically, 19 firefighters were lost in this fire. Many questions remain regarding the decisions made that led to this tragic event, as well as how communication and preparation could be improved. The city of Yarnell has worked to adapt communication systems and disaster response preparedness as a result of this event.[111] Existing transportation system connections impact the ability of first responders to access areas in need during an emergency. Additionally, transportation system asset conditions may become increasingly worse as the occurrence of hazardous events continues to increase.

With ongoing changing conditions influenced by climate change, desert climates must prepare for both extreme heat and increasing occurrences of sharp blasts of cold weather.[112] Intensifying conditions may lead to increased need for rehabilitation and maintenance of existing transportation assets. Without additional engineering or design to alter roadways based on anticipated weather pattern changes, routine costs for transportation agencies will increase. **Figure 31** maps this megaregion.

[109] (OA US EPA, n.d.-e)
[110] ("Yarnell Hill Fire Report Released," 2013)
[111] ("Yarnell Hill Fire Report Released," 2013)
[112] (Meko, 2019)

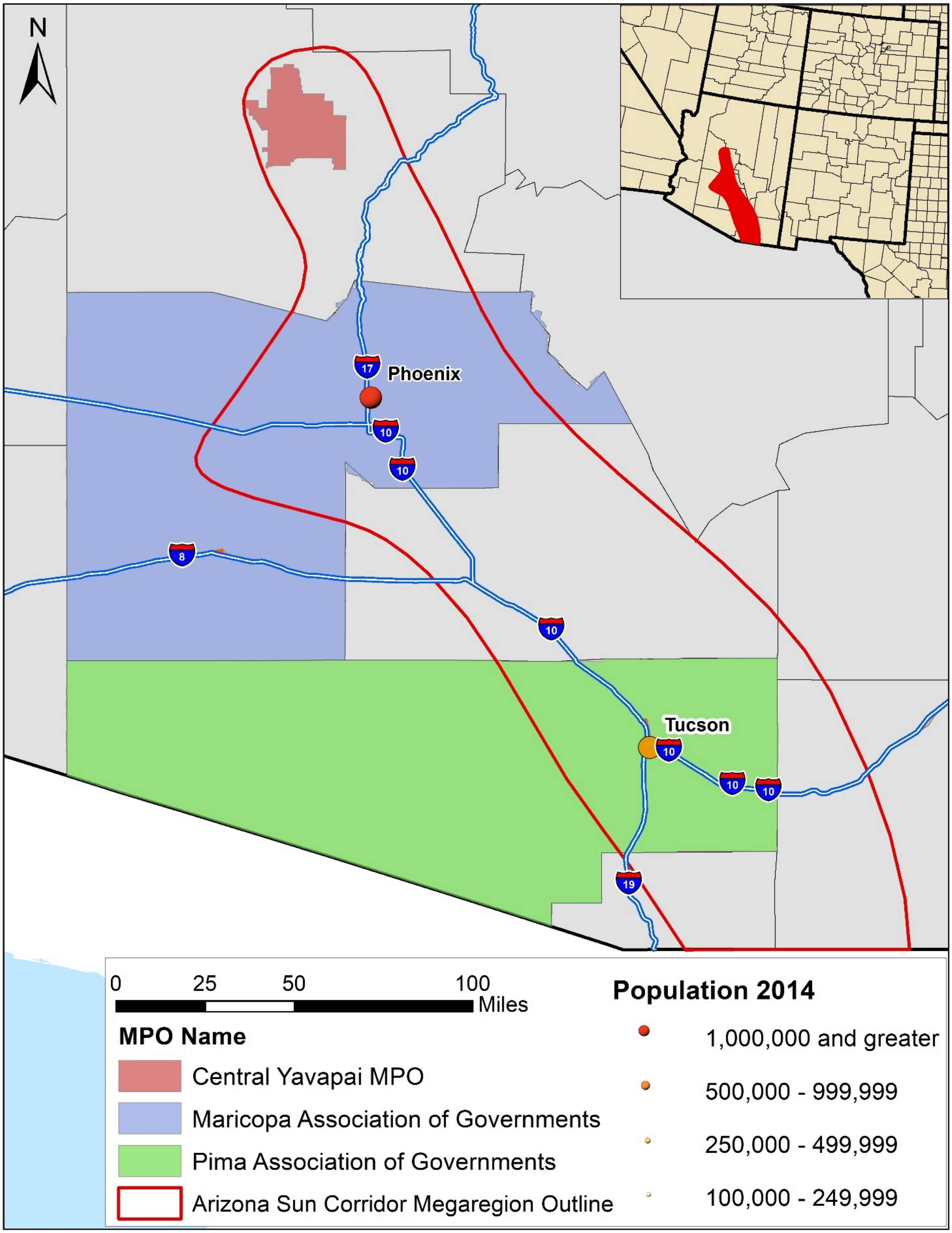

Figure 31: Arizona Sun Corridor Megaregion reference map.

ARIZONA SUN CORRIDOR

Principal Cities
1. Phoenix, Arizona
2. Tucson, Arizona

Fast Facts
2000 Population: 4.7M
2010 Population: 5.6M
Projected 2050 Population: 12.3M
Percent of U.S. GDP (2005): 2%
Percent of U.S. Population (2010): 2%

Transportation Governance Structures
Number of State Organizations: 1
MPOs: 3
Counties: 8

Most Common Natural Disaster Threats
Heat waves, flooding, wildfire.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: Arizona Department of Transportation (ADOT)
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: ADOT conducted a study to identify sections of major highways that are vulnerable to high temperatures and potential storms. The highway corridor included in this study connects Nogales, Tucson, Phoenix, and Flagstaff. The team evaluated surrounding geography characteristics across the state to understand potential differences in impact and levels of vulnerability. ADOT is using the outcome of this pilot program to develop a way to efficiently invest funds in the most vulnerable areas, and to integrate resilience to disaster events into the asset management and life cycle planning process.[113]

[113] (FHWA, n.d.-a)

5.2 Cascadia

The Cascadia Megaregion (**Figure 32**) is home to the Cascade Mountain Range and known for its wet winters and mild temperature summers. Gradual temperature changes have led to a decrease in the amount of total snowfall precipitation, and a change in precipitation patterns year-round.[114] Projections indicate that the frequency of summer precipitation events will decrease, but the amount of rain per event will increase. The projected increase in global sea levels will dramatically impact existing high populations of people and infrastructure that are concentrated in and around the Seattle area. The EPA notes that "Flooding, seawater inundation, and erosion are expected to threaten coastal infrastructure, including properties, highways, railways, wastewater treatment plants, stormwater outfalls, and ferry terminals."[115] Coastline erosion also increases the vulnerability of transportation infrastructure to storm events. Flooding, erosion, and increased intensity of rain events can lead to very dangerous secondary reactions, such as mudslides.

In March 2014, a deadly mudslide overtook an entire neighborhood in Oso, Washington, killing 44 people and making it the deadliest mudslide event in U.S. history.[116] In addition to its devastating human impacts, the mudslide made major damage to portions of State Highway 530. Reporters and scientists claim multiple factors contributed this event, including local development, logging industries, and mudslide events from previous years.[117] One element of this issue is pervasive no matter the number of contributing factors: rain events continue to increase in intensity and contribute to the occurrence of known risks like mudslide and landslides.[118] Transportation officials in the Pacific Northwest will be increasingly forced to grapple with the realities of increased risks of flooding, erosion, and landslides affecting roadways and other transportation infrastructure.

[114] (OA US EPA, n.d.-c)
[115] (OA US EPA, n.d.-c)
[116] (Cornwall, 2014)
[117] (Cornwall, 2014)
[118] (Holthaus, 2014)

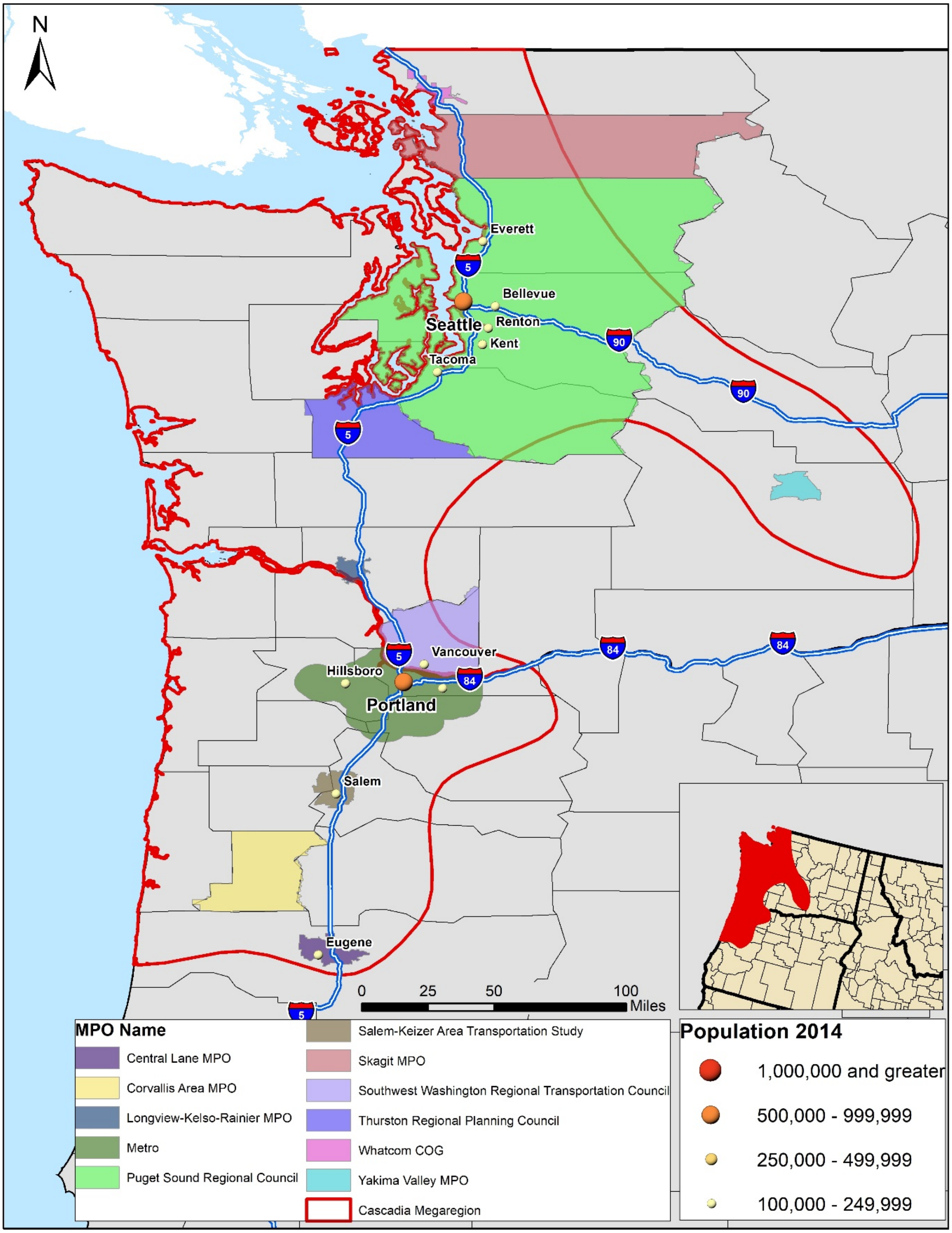

Figure 32: Cascadia Megaregion reference map.

CASCADIA

Principal Cities
1. Seattle, Washington
2. Portland, Oregon
3. Vancouver, British Columbia (not pictured)

Transportation Governance Structures
Number of State Organizations: 2
MPOs: 11
Counties: 34

Fast Facts
2000 Population: 7.4M
2010 Population: 8.4M
Projected 2050 Population: 11.8M
Percent of U.S. GDP (2005): 3%
Percent of U.S. Population (2010): 3%

Most Common Natural Disaster Threats
Earthquakes, wildfires, volcanos, snowfall, flooding, landslides.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: Washington State Department of Transportation (WSDOT)
Grant: Vulnerability Assessments (2010–2011)
Outcomes: WSDOT staff evaluated all state-owned highways and transportation assets for climate vulnerability to assess future facility risk. Through a close partnership with the University of Washington, WSDOT modeled future vulnerability based on three different types of climates scenarios that included changes in sea level rise, frequency and amount of rain, and extreme events such as increases in wildfires, storms, and temperature changes.[119]

Agency: Oregon Department of Transportation (ODOT) & Washington State Department of Transportation (WSDOT)
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: WSDOT worked in a multi-agency effort to assess a highly flood-prone region and identify flood risk reduction strategies. The project highlights the importance of collaboration across different transportation agencies in the state.[120] ODOT evaluated the vulnerability of highway infrastructure to extreme weather impacts like flooding, landslides, high sea levels and coastal erosion. The team created a GIS-based asset management system to develop adaptation strategies for specific roadways.[121]

Agency: Oregon Department of Transportation (ODOT)
Grant: Nature-based Resilience for Coastal Highways (2016–2017)
Outcomes: ODOT developed designs to reduce coastal erosion and vulnerability to storms on three major sections of the coastal highway (US 101).
They compared the effectiveness of multiple design strategies to develop recommendations for nature-based solutions.[122]

---

[119] (FHWA, WSDOT, n.d.-a)
[120] (FHWA, WSDOT, n.d.-b)
[121] (FHWA, ODOT, n.d.)
[122] (U.S. DOT, n.d.-d)

5.3 Front Range

The Front Range Megaregion (**Figure 33**) falls within the southwestern region of the U.S. The southwest includes a diverse range of geographies, including deserts, vast valleys, and mountain ranges. Increasing severity and risks of drought threaten the Front Range Megaregion, in addition to increased risks of wildfires and flooding.[123] Warming temperatures have decreased the amount of snowpack in Colorado and New Mexico during springtime, and is impacting levels of river flow.[124] Early avalanches are also increasing in likelihood, threatening early closures of ski resorts and mountain-related activities. Changes in levels of precipitation and wildfires implicate changes in biodiversity, forestation, and agricultural practices. Increases in intensity of snowstorms and ice can decrease visibility for travelers of all modes and increase the risk of crashes. Transportation department budgets may see an increased need for maintenance and rehabilitation from impacts of snow and ice.

Areas in and around the Front Range Megaregion have suffered from intense snowstorms. In March 2019, the governor of Colorado declared an emergency as a bomb cyclone made its way through Northern Colorado. The storm led to closed roads, over 20 inches of snow in some areas, hundreds of car accidents, thousands of flights diverted or canceled at the Denver International Airport, and avalanche warnings in the mountains.[125] High levels of snow and wind led to low levels of visibility on roads and tractor-trailers getting swept sideways.[126]

In addition to managing unexpected intense windstorms, the cities and regions in the Front Range Megaregion manage threats of wildfires. In May and June of 2018, parts of southern Colorado and northern New Mexico were forced to evacuate due to two raging wildfires that covered about 17,000 acres.[127] Hundreds of residents evacuated their homes and communities. Subsequent effects of wildfires include increased potential for flooding, as the ground is unable to absorb as much water. Transportation officials in the Front Range Megaregion will continually face diverse types of threats resulting from the megaregion's geographical variation.

[123] (OA US EPA, n.d.-e)
[124] (U.S. Global Change Research Program, n.d.)
[125] (Murray, 2019)
[126] (Murray, 2019)
[127] (O'Brien & Szekely, 400AD)

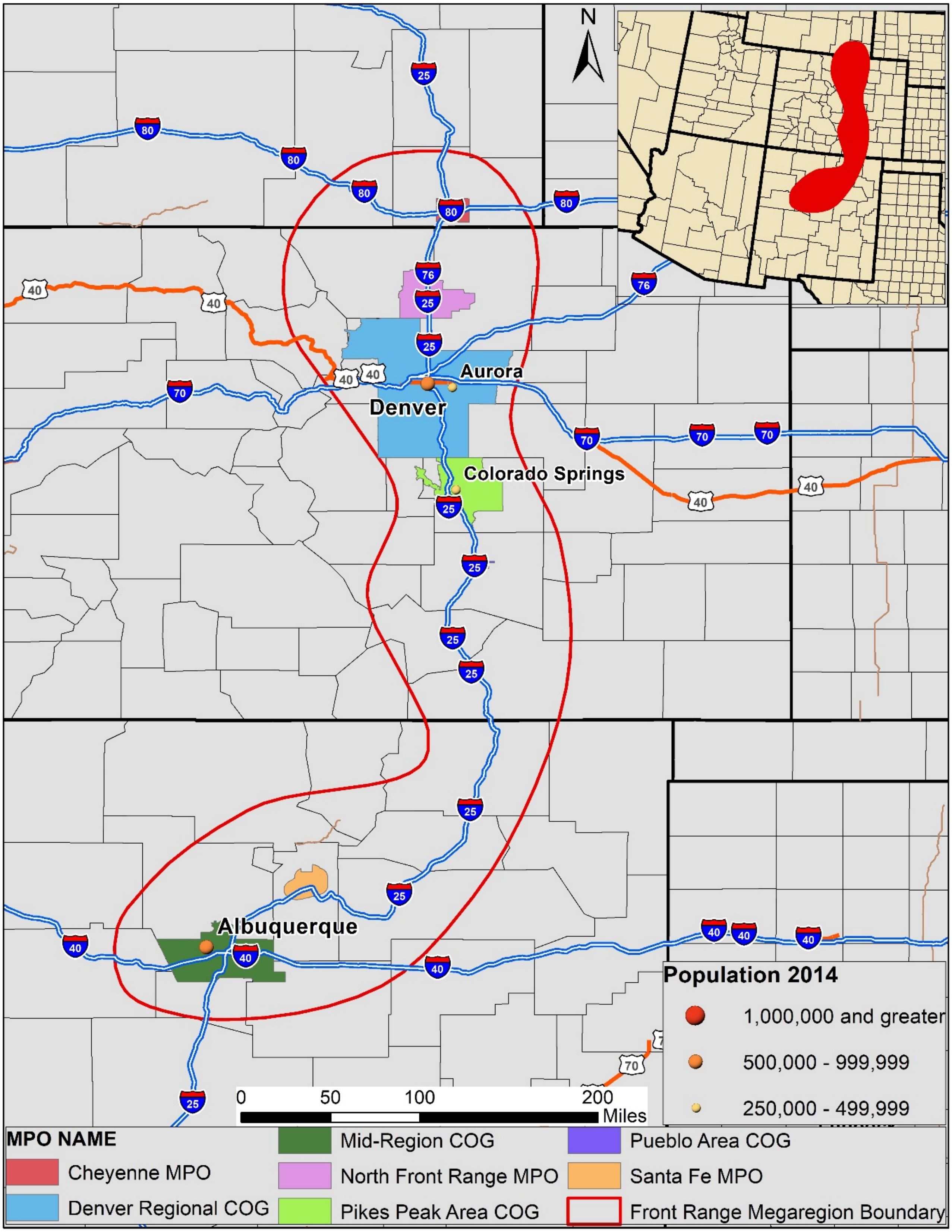

Figure 33: Front Range Megaregion reference map.

FRONT RANGE

Principal Cities
1. Albuquerque, New Mexico
2. Santa Fe, New Mexico
3. Colorado Springs, Colorado
4. Denver, Colorado

Transportation Governance Structures
Number of State Organizations: 3
MPOs: 7
Counties: 30

Government Organizational Structures
2000 Population: 4.7M
2010 Population: 5.5M
Projected 2050 Population: 10.2M
Percent of U.S. GDP (2005): 2%
Percent of U.S. Population (2010): 2%

Most Common Natural Disaster Threats
Heat waves and wildfires in the southern end; snowfall, flooding, tornados, landslides in the central and northern parts of the megaregion.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: FHWA, Transportation Engineering Approaches to Climate Resiliency Project
Grant: Wildfire and Precipitation Impacts to a Culvert: US 34 to Canyon Cove Lane (2013–2015)
Outcomes: This project was one of nine engineering case studies conducted to evaluate adaptation strategies to raise awareness of the importance of climate resilience for transportation infrastructure. The study focused on the impacts of wildfires and rain on highway stream crossing assets. The purpose of this study was to isolate the impacts of one particular asset and evaluate primary and secondary impacts of flooding and wildfire risks on transportation assets. This project contributes to the case study literature on impacts of wildfires on transportation infrastructure.[128]

Agency: Mid-Region MPO
Grant: Scenario Planning (2015)
Outcomes: The Mid-Region MPO facilitated a multi-agency initiative to integrate climate change and adaptation strategies into transportation and land use scenario planning. The goal of the scenario planning process was to understand how the region could reduce overall greenhouse gas emissions and prepare for potential future impacts of climate change. Outcomes of this initiative were integrated into the MPO long-range transportation plan.[129]

[128] (FHWA, n.d.-b)
[129] (FHWA, n.d.-c)

5.4 Gulf Coast

The Gulf Coast Megaregion (**Figure 34**) is highly susceptible to hurricane events along the coast, as evidenced by the increase in frequency and intensity of hurricane events in the past decade (as was discussed in Chapter 4). Hurricane events lead to transportation problems preceding an event from evacuations, and subsequently frequently lead to damaged roadways and bridges, as well as inland flooding.[130] This megaregion wraps around the Gulf of Mexico, making the entire megaregion vulnerable to tropical cyclone paths. Tropical storms are not concentrated to one specific region and can gain more momentum after moving across the warm Gulf waters. For example, in 2001 Tropical Storm Allison made initial landfall in Freeport, Texas, and traveled along the southern coast of Texas and parts of Louisiana.[131]

The Gulf Coast Megaregion has received much attention for the destructive hurricanes it has endured over the past two decades, including but not limited to Hurricane Harvey (2017), Hurricane Ike (2008), Hurricane Rita (2005), and Hurricane Katrina (2005).[132] Impacts of these disaster events have devastated many communities, which has served as a catalyst for federally funded pilot programs to study adaptation and resilience of transportation infrastructure systems. The Gulf Coast Megaregion is a collective of major economic gateway cities that connect the United States to Mexico, and cities that serve as primary hubs in the nation for petroleum refineries. A few days' closures in these industries have ripple effects across the supply chain of transportation, logistics, and retail industries.[133] Heavy rainfall alone can also have dramatic consequences in terms of roadway accidents. The FHWA notes that "Each year, 75 percent of weather-related vehicle crashes occur on wet pavement and 47 percent happen during rainfall."[134] Cities along the Gulf Coast Megaregion may experience a unique sense of urgency to mitigate the impacts on transportation assets of future storm events and sea level rise, given the increasing number of disaster events and the megaregion's economic significance to the nation.

[130] (FHWA Road Management Operations, n.d.-a)
[131] (NOAA, National Hurricane Center and Central Pacific Hurricane Center, n.d.)
[132] (NOAA, National Hurricane Center and Central Pacific Hurricane Center, n.d.)
[133] (April U, 2018)
[134] (FHWA Road Management Operations, n.d.-b)

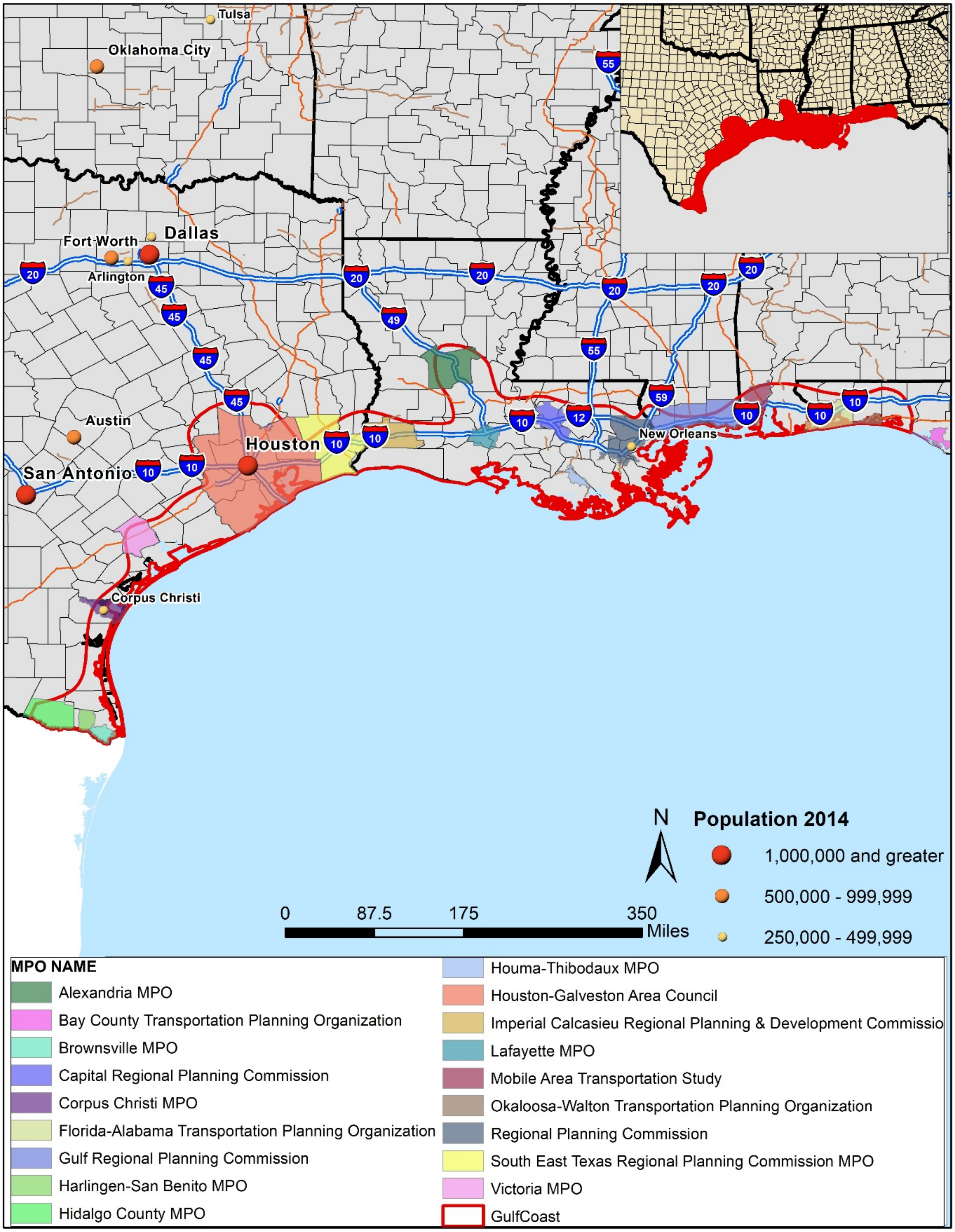

Figure 34: Gulf Coast Megaregion reference map.

GULF COAST

Principal Cities
1. Houston, Texas
2. New Orleans, Louisiana
3. Baton Rouge, Louisiana

Transportation Governance Structures
Number of State Organizations: 5
MPOs: 19
Counties: 75

Government Organizational Structures
2000 Population: 11.7M
2010 Population: 13.3M
Projected 2050 Population: 23.7M
Percent of U.S. GDP (2005): 4%
Percent of U.S. Population (2010): 4%

Most Common Natural Disaster Threats
Hurricanes, wildfires, floods, tornados, heat waves.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: Houston-Galveston Area Council (H-GAC)
Grant: Resilience and Durability to Extreme Weather (2018–2020)
Outcomes: H-GAC participated in a multi-agency partnership to develop strategies and recommendations to improve resiliency of transportation infrastructure on critical local and regional roadways. Projects and recommendations will be integrated into the long-range regional transportation plan and will be disseminated to local and regional agencies.[135]

Agency: Corpus Christi MPO and Mississippi DOT
Grant: Resilience and Durability to Extreme Weather (2018–2020)
Outcomes: The intended outcome was the design of a nature-based shoreline protection feature to improve resilience along the coast in the Corpus Christi region, specifically to mitigate shoreline erosion and flooding/inundation. The Mississippi DOT is testing the use of vegetated berms to protect a bridge from future coastal storm surges.[136]

Agency: FHWA, Transportation Engineering Approaches to Climate Resiliency Project
Grant: Over-washing from Sea Level Rise and Storm Surge: US 98 on Okaloosa Island, Florida;
Outcomes: FHWA published *Sea Level Rise and Storm Surge Impacts on a Coastal Bridge: I-10 Bayway, Mobile Bay, Alabama*, one of nine studies conducted to evaluate specific solutions for climate adaptation and resilience to transportation infrastructure.[137]

Agency: United State Department of Transportation (USDOT)
Grant: Gulf Coast Study Phases 1 (completed in 2008) and 2 (competed in 2015)
Outcomes: Both phases of this project produced tools for identifying vulnerabilities and integrating resilience to climate change in transportation infrastructure planning, focusing on coastal regions of Louisiana and Alabama.[138]

[135] (U.S. DOT, n.d.-d)
[136] (U.S. DOT, n.d.-d)
[137] (U.S. DOT, n.d.-d)
[138] (U.S. DOT, n.d.-c)

5.5 Midwest/Great Lakes

The Midwest/Great Lake Megaregion (**Figures 35 and 36**) is a large megaregion that encompasses many urban centers, surrounded by lakes, forests, and major national river systems. Average temperatures in the Midwest have progressively gotten warmer, and climate change forecasts predict warmer summers, and more intense and more frequent rain events, particularly in spring and winter months. The EPA reports that "The Midwest is subject to extremely cold air masses from the far north, and warm, humid air masses from the Gulf of Mexico, resulting in a wide range of both temperature and precipitation extremes."[139] With increased rain events, potential flooding and drainage issues arise. If winter storms become more intense, transportation agencies located in the Midwest will become more vulnerable to changing asset management practices and potential shutdowns during storm events.[140] The existing river systems pose threats for increased flooding issues, as seen in the 2019 spring season.

While the river systems in the Midwest are assets for communities within the megaregion, they are also vulnerable to flooding. Between March and June of 2019, the Illinois, Missouri, Mississippi, and Arkansas rivers all rose to levels unseen since 1993.[141] Consistent and intense rain events resulted in flash floods and rising water levels in all major rivers. In addition to creating a potential health risk to drinking water and an inability to access parts of the transportation system, farmers suffered flooded crop fields and may have been unable to plant crops for the following season. Massive flooding throughout the Midwest was a result of both consistent and heavy rain events in combination with a cold winter that led to ice and snow melting later than usual. These two factors resulted in the flooding taking longer to subside.[142] The economic centers of the Midwest will be forced to evaluate the impact of disaster events and climate related issues to the megaregion. Transportation officials will need to work closely across levels of government to develop sustainable practices to mitigate flood risks and adapt to changing circumstances.

[139] (OA US EPA, n.d.-a)
[140] (OA US EPA, n.d.-f)
[141] (Irfan, 2019)
[142] (Irfan, 2019)

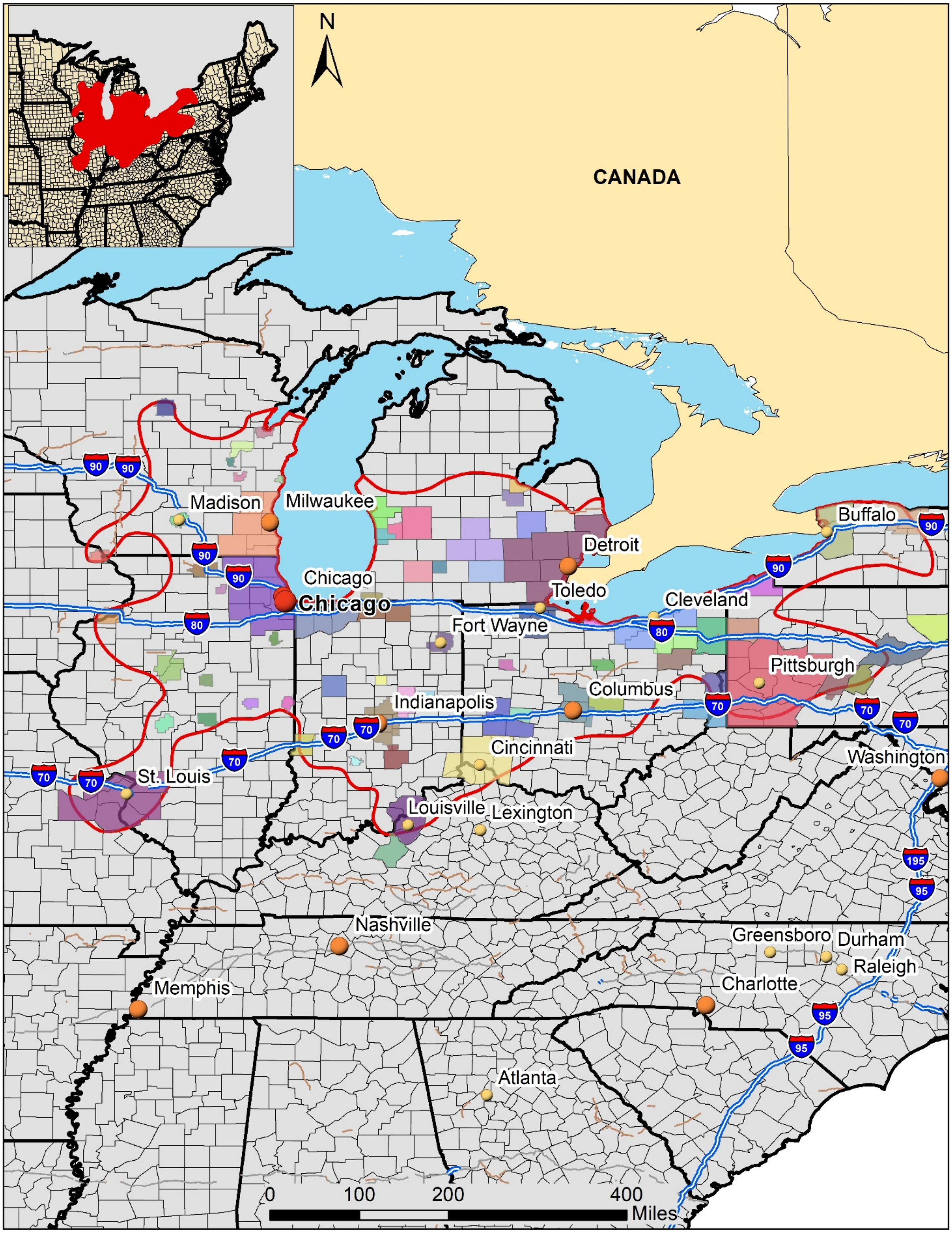

Figure 35: Midwest/Great Lakes Megaregion reference map.

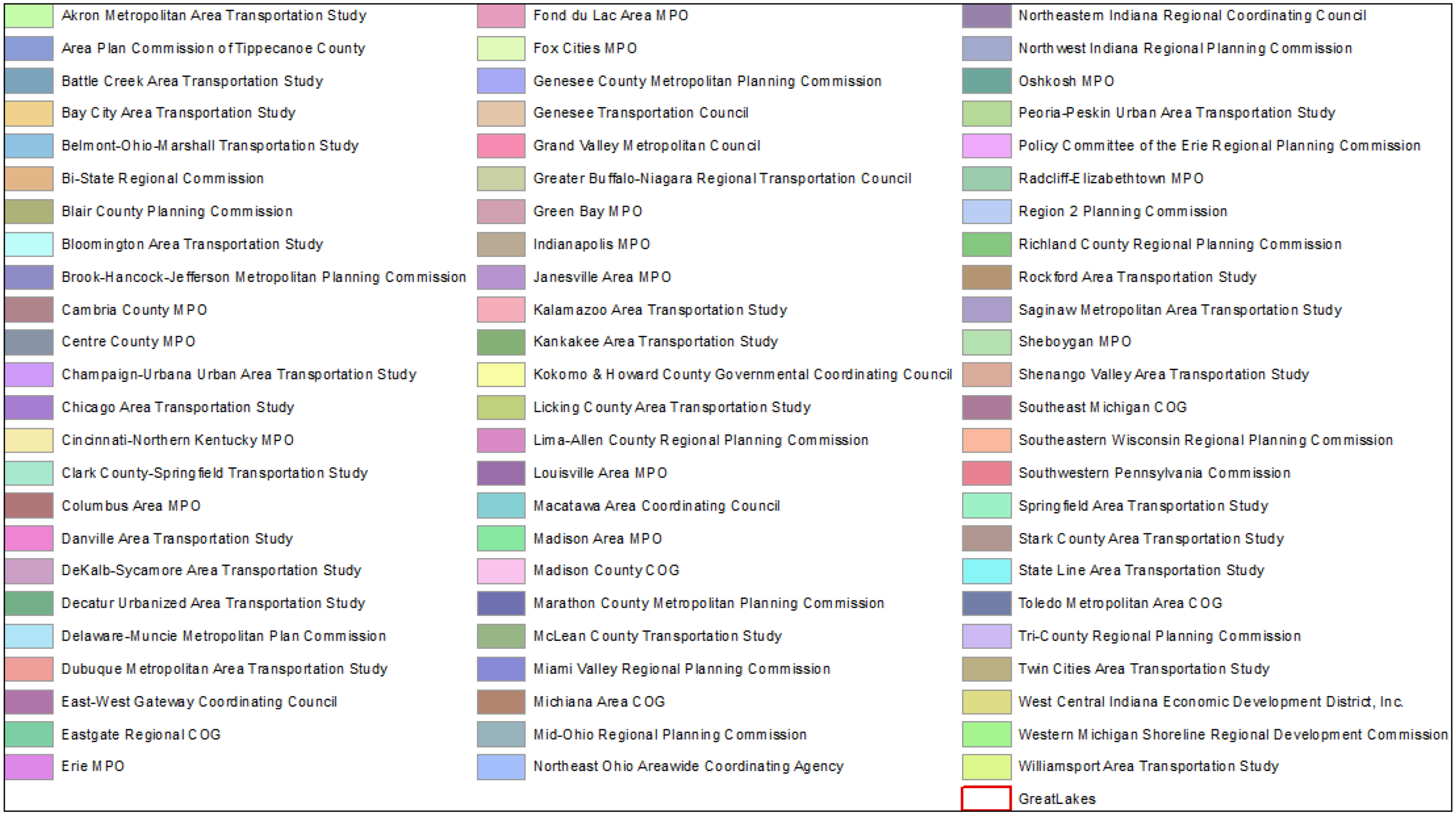

Figure 36: Legend of MPOs in the Midwest/Great Lakes Megaregion.

Principal Cities
1. Chicago, Illinois
2. Detroit, Michigan
3. Pittsburgh, Pennsylvania
4. Cleveland, Ohio
5. Minneapolis, Minnesota
6. St. Louis, Missouri
7. Indianapolis, Indiana

Government Organizational Structures
2000 Population: 53.7M
2010 Population: 55.5M
Projected 2050 Population: 71.3M
Percent of U.S. GDP (2005): 17%
Percent of U.S. Population (2010): 18%

Transportation Governance Structures
Number of State Organizations: 11
MPOs: 71
Counties: 388

Most Common Natural Disaster Threats
Tornados, heat waves, flooding, snowfall hazards, landslides.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: Michigan DOT (MDOT)
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: MDOT conducted an analysis using existing asset management information and climate change projections to identify vulnerable state-owned and operated assets. After identifying the most vulnerable assets, MDOT began developing adaptation strategies. One of the findings of this project found that the most at-risk transportation assets are located in the same areas of the state's larger urban centers.[143]

Agency: Bi-State Regional Commission (Iowa/Illinois MPO)
Grant: Resilience and Durability to Extreme Weather (2018–2020)
Outcomes: The bi-state regional commission used the FHWA Vulnerability Assessment Framework to conduct testing and develop strategies for addressing resilience and mitigation to climate threats. The project evaluated multiple modes in the region. The MPO will incorporate short- and long-term mitigation strategies developed during this project into the next long-range regional transportation plan.[144]

[143] (FWHA, MDOT, n.d.)
[144] (U.S. DOT, n.d.-d)

5.6 Northeast

The geography of the Northeast Megaregion (**Figures 37 and 38**) makes some of the nation's densest population centers highly vulnerable to sea level rise, increased storm surges, and increased intensity and frequency of precipitation events.[145] Increases in warmer temperatures and rain events are predicted throughout this megaregion, which could lead to damaging consequences as "the timing of winter and spring precipitation could lead to drought conditions in summer as warmer temperatures increase evaporation and accelerate snow melt."[146]

In late October of 2012, Superstorm Sandy made landfall close to Brigantine, New Jersey as a tropical cyclone, catalyzing storm surges along the coastline of New York and New Jersey.[147] In addition to being the second costliest tropical cyclone to impact the United States since 1900, Sandy caused 147 direct fatalities along the Atlantic coast. Preliminary estimates of cost of damage are approximately $50 billion, excluding disruption of business and transport of goods. Inundation levels of 4 to 9 ft were recorded around New York City and New Jersey. While New York and New Jersey experienced the highest storm surges and inundation levels, Sandy impacted sea levels and flooding from rainfall along the Atlantic coast. The New York City Metropolitan Transit Authority reported approximately $5 million in damages, including eight tunnels inundated and access between Manhattan and Brooklyn suspended for multiple weeks after the storm.[148] In addition to an interruption in service for commuter transportation, the movement of goods to and through the largest seaport on the east coast was interrupted for 7–8 days, impacting the delivery of freight cargo that are integral to the functioning of the northeast region.[149] The supply chain disruption led some import vessels to deliver goods to nearby ports in the region, creating a longer route for goods to be delivered to their intended destination. Transportation officials will continue to be challenged with various adaptation and mitigation needs within varying seasons throughout the year. The coordination between the large number of adjacent transportation agencies in the megaregion will require continued extensive coordination in years to come.

[145] (OA US EPA, n.d.-b)
[146] (OA US EPA, n.d.-b)
[147] (Blake, Kimberlain, Berg, Cangialosi, & Beven II, 2013)
[148] (Blake, Kimberlain, Berg, Cangialosi, & Beven II, 2013)
[149] (Leach, 2012)

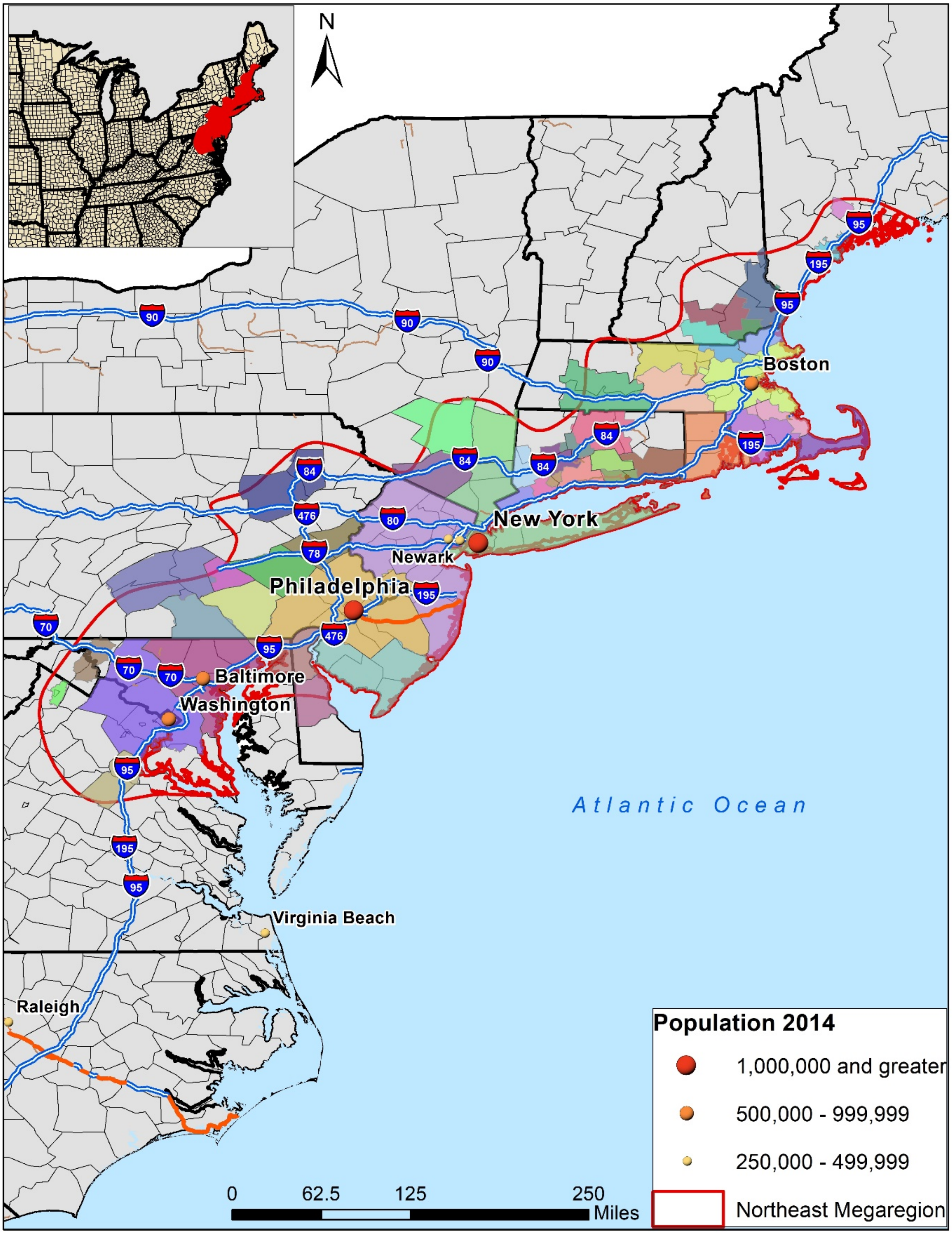

Figure 37: Northeast Megaregion reference map.

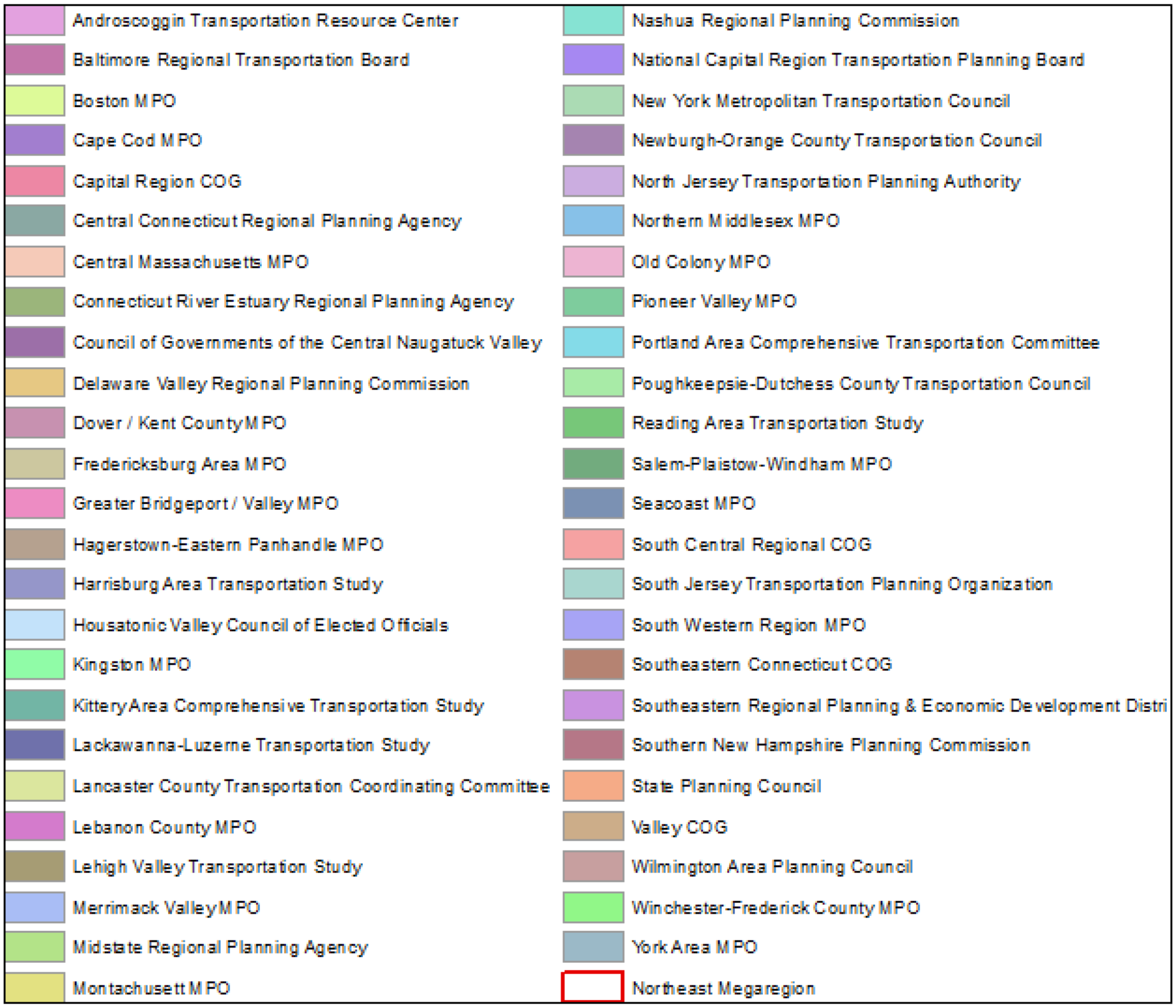

Figure 38: Legend of MPOs in Northeast Megaregion.

NORTHEAST

Principal Cities
1. Boston, Massachusetts
2. New York, New York
3. Philadelphia, Pennsylvania
4. Baltimore, Maryland
5. Washington D.C.

Transportation Governance Structures
Number of State Organizations: 12
MPOs: 49
Counties: 142

Government Organizational Structures
2000 Population: 49.5M
2010 Population: 58.4M
Projected 2050 Population: 70.8M
Percent of U.S. GDP: (2010): 20%
Percent of U.S. Population (2010): 17%

Most Common Natural Disaster Threats
Tornados, flooding, hurricanes, wildfires, heat waves, snowfall hazards.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: Virginia DOT & New Jersey DOT/North Jersey Transportation Planning Authority (NJTPA)
Grant: Vulnerability Assessments (2010–2011)
Outcomes: The NJTPA developed a GIS-based vulnerability assessment focusing on multi-modal infrastructure in central New Jersey and along the Atlantic coast. Transportation officials are using the outcomes of this study to continue evaluating smaller geographical areas of high vulnerability in the state, and to develop an adaptation plan.[150] The Virginia DOT led a multi-agency effort to evaluate how different climate change scenarios might impact future transportation priorities based on anticipated growth in population and industry.[151]

Agency: Connecticut DOT (CDOT), Maine DOT (MaineDOT), Maryland State Highway Administration (SHA), Massachusetts DOT (MassDOT), New York State DOT (NYSDOT)
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: CDOT's work focused specifically on bridges and culverts most at risk of inland flooding impacts from heavy rainfall events. Lessons learned include the need to identify inefficiencies in existing processes, ways to better coordinate with stakeholders, and the need to integrate economic analysis with risk assessments for critical highway structures.[152] NYSDOT created a decision-making tool to prioritize needed rehabilitation of vulnerable transportation assets based on climate risk and economic costs and benefits.[153]

The MaineDOT project served as a continuation of an earlier NOAA-funded project. MaineDOT used FHWA pilot funding to model multiple storm surge and sea level rise scenarios to test

---

[150] (FHWA, NJTPA, n.d.)
[151] (FWHA, VDOT, n.d.)
[152] (FHWA, CDOT, n.d.)
[153] (FHWA, NYSDOT, n.d.)

impacts of state-owned transportation assets in six coastal towns. Impacts and insights of the pilot work can be extended to other parts of Maine.[154]

MassDOT's pilot project focused on understanding how future climate change trends might impact the I-93 Century Artery/Tunnel in Boston. Through creating an inventory of assets that are considered part of the Century Artery/Tunnel network, the group was able to identify levels of vulnerability to disaster events and sea level rise and begin identifying potential adaptation strategies for the more critical parts of the network.[155]

Maryland SHA evaluated two counties with differing geographical characteristics to evaluate vulnerability to climate impacts such as flooding, storm surges and sea level rise. Outcomes of this project were used to challenge existing planning, design, and asset management practices to incorporate more resilience methods.[156]

Agency: Delaware DOT (DelDOT), Maine DOT, and New Hampshire DOT (NHDOT)
Grant: Nature-based Resilience for Coastal Highways (2016–2017)
Outcomes: DelDOT focused on identifying opportunities to incorporate nature-based solutions to increase the resilience of State Route 1, a critical road that is vulnerable to sea level rise and flooding. Strategies were identified that could be extended and incorporated to multiple segments of the roadway in the future.[157] MaineDOT and NHDOT partnered to investigate potential for green infrastructure to alleviate chronic impacts of climate change issues to critical state roadways. Both DOTs modeled multiple alternative scenarios to test the proof of concept and have identified next steps to continue the work.[158]

Agency: MassDOT, Pennsylvania DOT (PennDOT)
Grant: Resilience and Durability to Extreme Weather (2018–2020)
Outcomes: PennDOT is in the process of using cost-benefit analysis and testing adaptive structural designs to make transportation infrastructure more resilient to threats of flooding and extreme weather events. MassDOT is in the process of analyzing the vulnerability of transportation infrastructure to inland flooding and integrating identified outcomes into ongoing asset management practices.[159]

[154] (FHWA, MaineDOT, n.d.)
[155] (FHWA, MassDOT, n.d.)
[156] (FHWA, MSHA, n.d.)
[157] (FHWA, DelDOT, n.d.)
[158] (FHWA, MaineDOT, New Hampshire DOT, n.d.)
[159] (U.S. DOT, n.d.-d)

5.7 Northern California

The geography in the Northern California Megaregion (**Figure 39**) encompasses regions most vulnerable to coastal threats, as well as more inland mountainous and forested regions. The megaregion's diverse geography increases vulnerability to many types of climate change, such as sea level rise, storm surges along the coast, flooding during storm events, wildfires, increased changes in precipitation patterns, and rising temperatures that cause snowcap melt and water runoff.[160] One study predicted an over 15% decrease in precipitation in California between 2020 and 2030, which would have dramatic impacts to the agriculture sector.[161] Decreased precipitation combined with increased heat and dry land create a situation prime for wildfire risk. The Climate Reality Project states that most of the ten largest fires in California have occurred after 2004.[162] In 2018, the California Department of Forestry and Fire Protection received dispatch calls for 6,284 events.[163]

On November 8, 2018, the deadliest and most destructive fire in California's history began in Northern California. After 17 days of combatting the fire, the disaster event resulted in a tragic loss of at least 85 lives.[164] After the fire burned through 153,000 acres, three days of rain ultimately helped firefighters gain enough momentum to bring the fire to a halt. Dry land and high temperatures combined with high winds to create the ideal set of conditions for the fire to spread quickly. In addition to the horrifying realities facing displaced residents and incinerated communities, remains of the blaze led to massive amounts of hazardous and potentially toxic debris on roadways. The rainfall led to subsequent concerns for flash flooding and the spreading of hazardous debris.[165] Transportation networks are critical for connecting people in need to services and shelter, in addition to providing necessary access for emergency response teams. Transportation officials will need to confront the reality of funding safe removal of hazardous debris, in addition to heightened maintenance costs from roadway repair that may be necessary following these types of events.

[160] (OA US EPA, n.d.-e)
[161] ("How Climate Change Is Affecting California," 2018)
[162] ("How Climate Change Is Affecting California," 2018)
[163] ("Welcome to Stats & Events," n.d.)
[164] (Wootson Jr, 2018)
[165] (Wootson Jr, 2018)

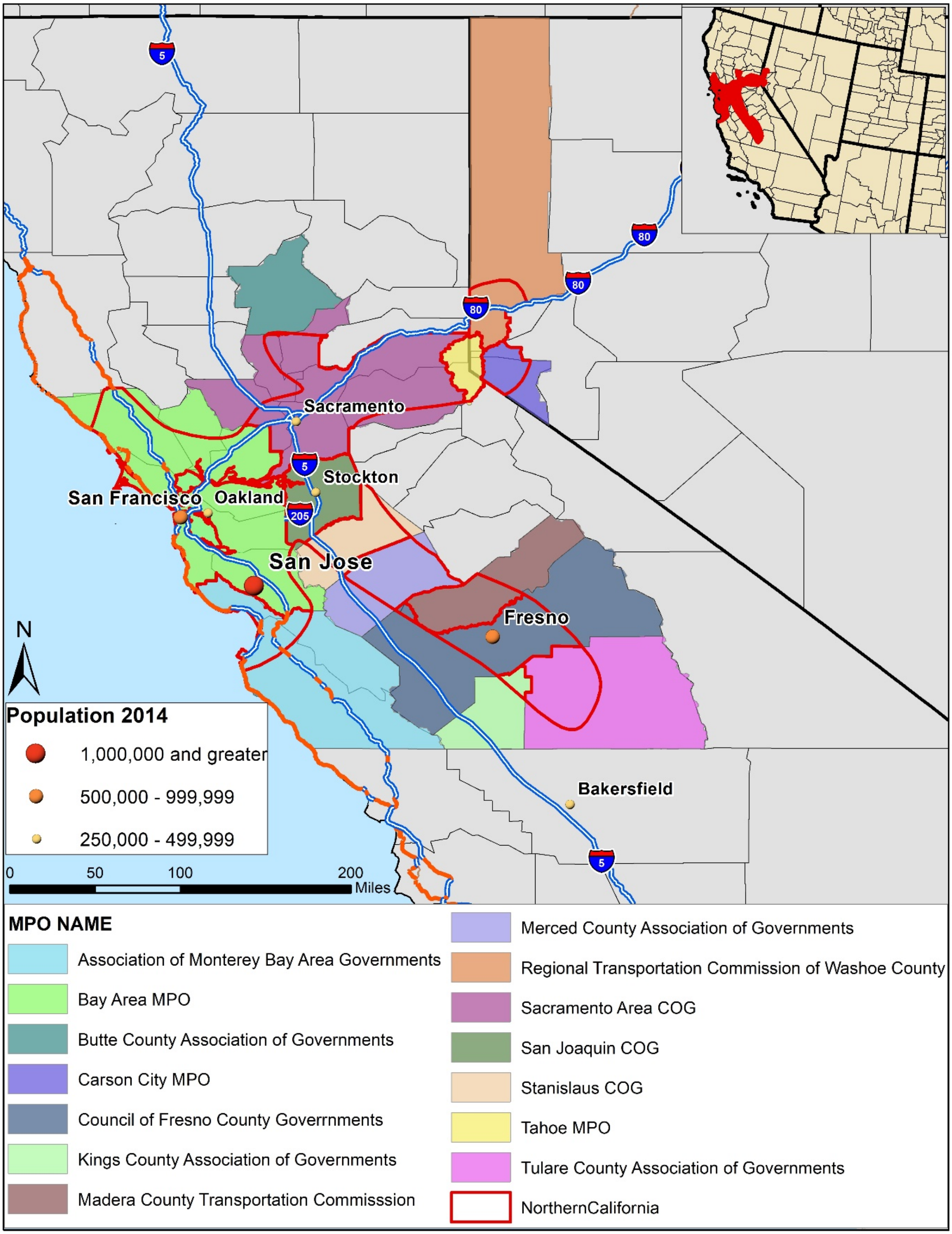

Figure 39: Northern California Megaregion reference map.

NORTHERN CALIFORNIA

Principal Cities
1. Oakland, California
2. Reno, Nevada
3. Sacramento, California
4. San Jose, California
5. San Francisco, California

Transportation Governance Structures
Number of State Organizations: 2
MPOs: 14
Counties: 31

Government Organizational Structures
2000 Population: 12.7M
2010 Population: 14M
Projected 2050 Population: 21.2M
Percent of U.S. GDP (2005): 5%
Percent of U.S. Population (2010): 5%

Most Common Natural Disaster Threats
Earthquakes, heat waves, flooding, wildfires, snowfall hazards, droughts, landslides.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: Metropolitan Transportation Commission (MTC)
Grant: Vulnerability Assessments (2010–2011)
Outcomes: This project evaluated four critical types of transportation infrastructure in the San Francisco Bay region: road, transit, operations and maintenance facilities, and active transportation networks. The project evaluated sea level rise, projected increased precipitation events, and seismic events. The group collected data to inform the results of a vulnerability assessment and identify asset types at highest risk. Adaptation strategies were developed for the regional transportation agency based on the outcomes of the vulnerability assessment.[166]

Agency: MTC, San Francisco Bay Conservation and Development Commissions, California DOT (Caltrans), San Francisco Bay Area Rapid Transit District
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: This multi-agency effort evaluated transportation infrastructure most vulnerable to sea level rise in the region and led to the development of a set of adaptation strategies for the identified assets. The types of infrastructure evaluated included a bridge connecting San Francisco to Oakland, a section of a state highway corridor, and the area encompassing the Oakland Coliseum. The outcomes of this effort are used to "inform regional and state policy and investment decisions," and are meant to provide a framework for projects moving forward.[167]

Agency: Caltrans
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: This pilot covered four counties within Caltrans District 1. It evaluated vulnerability of state transportation infrastructure throughout the district and studied secondary climate impacts to roadways. The team developed four location prototypes to develop adaptation options applicable throughout the district. Options were evaluated and prioritized for next steps in adaptation work progress.

[166] (FHWA, MTC, n.d.)
[167] (FHWA, MTC, n.d.)

5.8 Piedmont

The Piedmont Megaregion (**Figure 40**) spans four states, including cities closer to the east coast like Raleigh and Charlotte, North Carolina, and inland major metropolitan areas like Atlanta, Georgia. This megaregion is considered the northern part of the southeastern region of the U.S. and is vulnerable to hurricanes, flooding, wildfires, and tornados.[168] Inland parts of the southeastern U.S. are expected to experience an increase in the number of future warmer days compared to coastal regions. While southwestern parts of this region are expected to experience drier conditions, the northern end of the region is expected to experience longer wetter periods throughout the year.[169] Longer periods of rain intense rainfall can exacerbate existing issues with flooding.

In September 2009, many northern counties in Georgia experienced flooding from continuous rain events, leading to 500-year floods.[170] Over twenty counties were part of Federal Disaster Declarations.[171] Flooding in South Carolina closed I-95 in October 2015, making a major transport corridor inaccessible for several weeks because of high water levels.[172] In October 2016, Hurricane Matthew touched down in McClellanville, South Carolina, as a Category 1 hurricane.[173] The amount of resulting flooding from the hurricane led to 25 deaths in North Carolina and 3 in South Carolina. The hurricane had destructive impact on many areas of the Caribbean, and damage reported in the U.S. is estimated to be $10.3 billion. Levels of rainfall across North Carolina from Hurricane Matthew ranged between 6.5 to almost 19 inches; wind gusts ranged from 43 to 97 miles per hour (mph). South Carolina experienced wind gusts from 36 to 103 mph, and a range of 9 to 17 inches of rain. The Carolinas were affected by four other hurricanes in the 2016 season other than Hurricane Matthew.[174] Major transport corridors throughout this megaregion will become even more important to ensure connectivity to regions with varying vulnerabilities. MPOs could play a central role in collaborating with state DOTs and more rural areas to improve the resilience of existing transport systems.

---

[168] (OA US EPA, n.d.-d)
[169] (OA US EPA, n.d.-d)
[170] ("Georgia Disaster History," n.d.)
[171] ("Georgia Disaster History," n.d.)
[172] (National Centers for Environmental Information, n.d.-a)
[173] (NOAA, National Weather Service, n.d.)
[174] (NOAA, National Weather Service, n.d.)

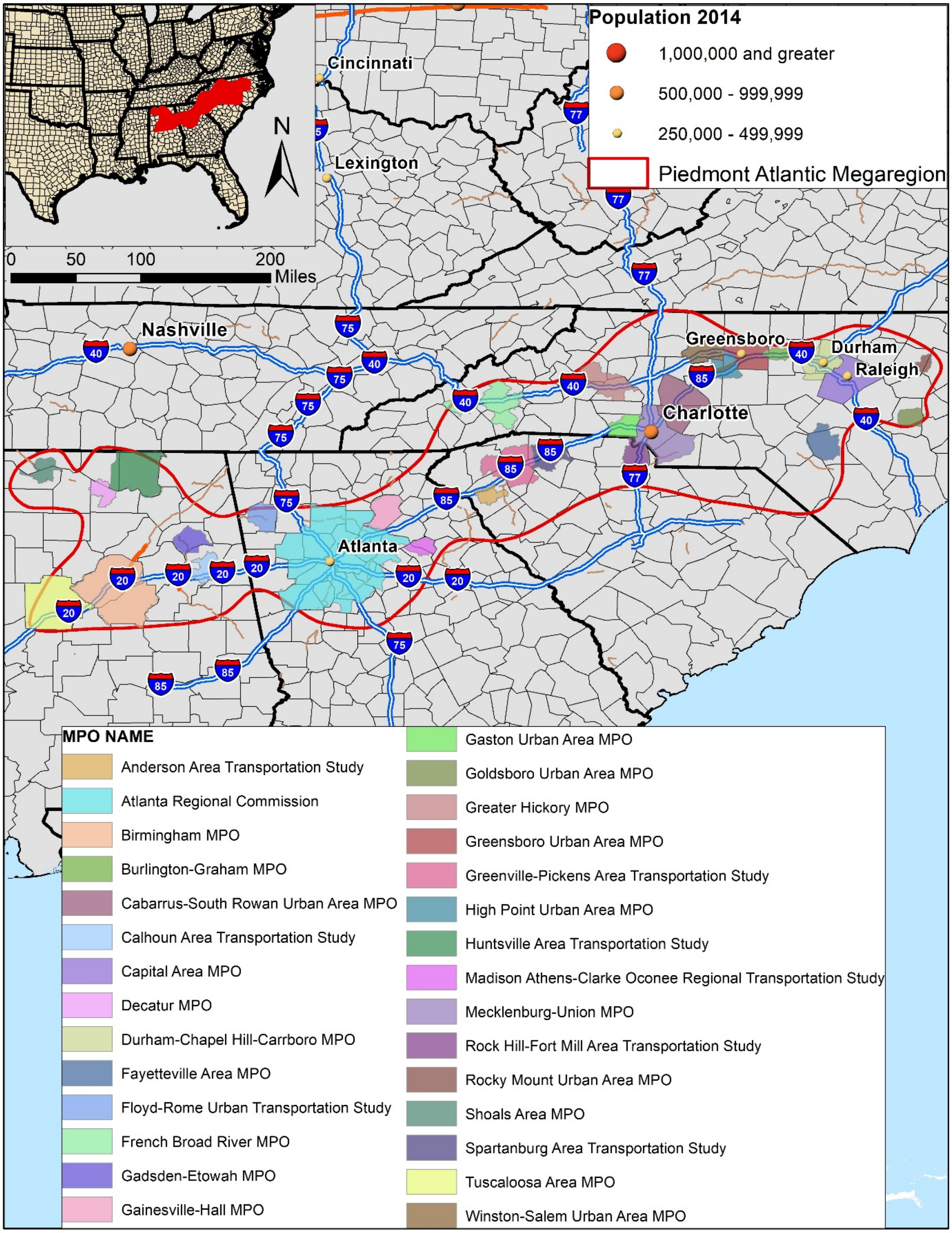

Figure 40: Piedmont Megaregion reference map.

PIEDMONT ATLANTIC

Principal Cities
1. Atlanta, Georgia
2. Birmingham, Alabama
3. Raleigh-Durham, North Carolina
4. Charlotte, North Carolina

Transportation Governance Structures
Number of State Organizations: 4
MPOs: 29 Counties: 121

Fast Facts
2000 Population: 14.8M
2010 Population: 17.6M
Projected 2050 Population: 31.3M
Percent of U.S. GDP (2005): 4%
Percent of U.S. Population (2010): 6%

Most Common Natural Disaster Threats
Flooding, heat waves, landslides, hurricanes, wildfires, tornados.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: Tennessee DOT (TDOT)
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: TDOT created a GIS-based database of critical assets and levels of vulnerability to all climate related weather events throughout the state. The project identified areas of highest vulnerability under future climate forecast scenarios. Results of this work will be integrated into the statewide risk-based transportation asset management plan.[175]

Agency: Atlanta Regional Commission (ARC)
Grant: Resilience and Durability to Extreme Weather (2018–2020)
Outcomes: ARC is in the process of conducting a high-level risk assessment of the Atlanta Region, and integrating practices to enhance resilience and durability of transportation infrastructure assets into ongoing agency operations such as monitoring asset performance or evaluating vulnerability and risk in the regional transport system. The project will begin integrating newly identified methods into ongoing planning and engineering processes.[176]

[175] (FHWA, TDOT, n.d.)
[176] (U.S. DOT, n.d.-d)

5.9 Southern California

The Southern California Megaregion (**Figure 41**) is part of the nation's driest and hottest climates, which is projected to experience an increase in number of hot days experienced each year.[177] The western part of the megaregion is bordered by the Pacific coast, with beach towns running down to the California-Mexico border. Smaller towns and cities separate Los Angeles and San Diego, but between the west and Las Vegas are parks, forests, and national and state preserves of various altitudes and sizes. Droughts are the most common natural disaster associated with western regions in California, due to decreased precipitation events along the coast. However, earthquakes, storm surges, and flooding continue to be major concerns for both coastal and inland communities. In January 2008, rainstorms and tornados led to flash flooding and landslides throughout the state.[178] In January 2007, the state experienced an agricultural freeze that impacted fruit and vegetable crops throughout the state.[179]

The severity of drought events in California has increased in the past few decades, impacting agricultural production and creating areas of high vulnerability to wildfires. By 2016, wildfires had damages over 100 million trees throughout California in the past five years. The six-year long drought continued into summer and fall of 2017, when wildfires spread outside of LA.[180] In addition to drought and wildfire activity, in January 2017, areas around San Diego were damaged by high winds, preceding an outbreak of 79 tornados that spread across about seven other southern states.[181] All of the disasters listed above had a cumulative cost that totaled over a billion dollars. The contiguity of MPOs in the Southern California Megaregion creates a perfect test case for how MPOs might collaborate with each other to play a larger role in planning for resilience transportation systems. Collaboration with the state DOT should also theoretically be easier to coordinate with because of the small number of entities compared to the number in other megaregions.

[177] (OA US EPA, n.d.-e)
[178] (National Centers for Environmental Information, n.d.-a)
[179] (National Centers for Environmental Information, n.d.-a)
[180] (National Centers for Environmental Information, n.d.-a)
[181] (National Centers for Environmental Information, n.d.-a)

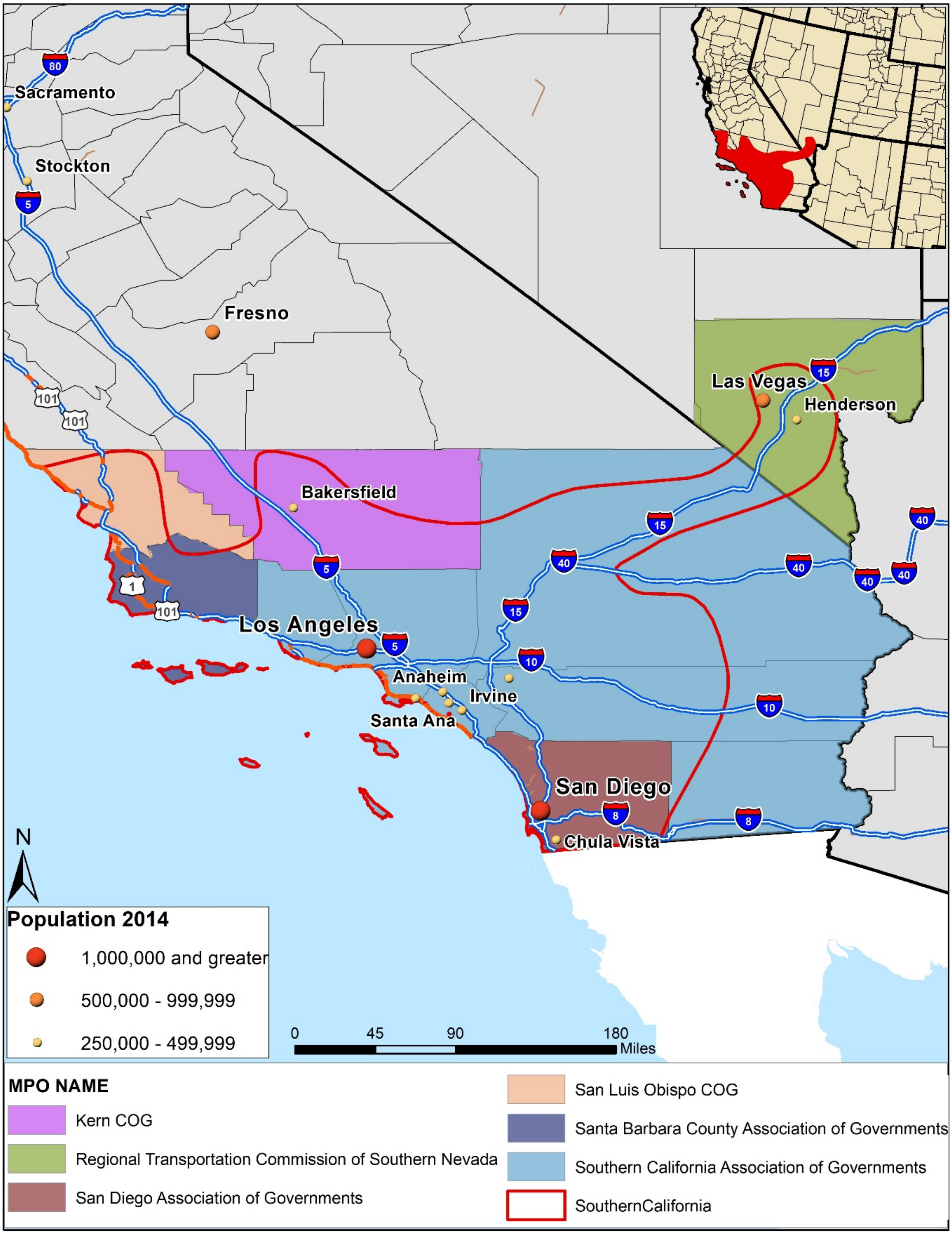

Figure 41: Southern California reference map.

SOUTHERN CALIFORNIA

Principal Cities
1. Los Angeles, California
2. San Diego, California
3. Anaheim, California
4. Long Beach, California
5. Las Vegas, Nevada

Transport Governance Structures
Number of State Organizations: 2
MPOs: 6
Counties: 10

Population Information
2000 Population: 21.8M
2010 Population: 24.4M
Projected 2050 Population: 39.4M
Percent of U.S. GDP (2005): 7%
Percent of U.S. Population (2010): 8%

Most Common Natural Disaster Threats
Hurricanes along the coastal areas. Inland megaregion counties experience issues of drought and flooding.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: California DOT (Caltrans)
Grant: Resilience and Durability to Extreme Weather (2018–2020)
Outcomes: The work conducted by Caltrans includes a statewide vulnerability and climate risk assessment. Types of climate impacts include changes to precipitation patterns, sea level rise, temperature increases, and increased vulnerability to wildfires. The second part of this project includes equipping transportation agencies throughout the state with tools for effective climate change communication. The ultimate goal of this grant is to put integrate outcomes into Caltrans agency practice.[182]

[182] (FHWA, n.d.-d)

5.10 Southern Florida

The entire Southern Florida Megaregion (**Figure 42**) is bordered by the coast, with the Atlantic Ocean to the east and the Gulf of Mexico to the west. With increasing frequency, Florida is the location of many expected locations of landfall for hurricanes reaching the United States. Coastal cities are vulnerable to hurricane and tropical storm disaster events, while inland counties and cities are more vulnerable to drought and flooding. The southeastern region of the U.S. is expected to see heavier rain patterns with increasing frequency and severity of hurricane events, in addition to extremely dry periods.[183] In 2012, the U.S. experienced its most extensive drought in over 80 years, leading to harvesting failure for agriculture production.[184] In contrast, March 2017 included an unexpected severe freeze, leading to the damage of many fruit crops across the megaregion.

Coastal areas are impacted by shoreline erosion and coastal flooding, requiring cities and regional agencies to reevaluate how land and water systems interact with each other.[185] The Southern Florida Megaregion spans approximately 150 miles from east to west, meaning that little land goes without vulnerability or risk to tropical storm disasters.[186] As sea levels continue to rise, storm surges are predicted to get higher and increase coastal flooding. The combination of ground subsidence and sea level rise makes coastal regions at highest risk for sea level rise and flooding.[187] In September 2017, Hurricane Irma made landfall in the Florida keys as a Category 4 hurricane.[188] The majority of the buildings in the areas were significantly damaged; 25% were completely destroyed. In addition to the devastating impacts to southern Florida, impacts of the storm traveled along the east coast. Northern Florida and coastal South Carolina experienced major coastal flooding resulting from intense storm surge.[189] Transport networks in regions like the Florida keys are particularly vulnerable to impacts of intense storm events, because the number of physical connections made to mainland Florida are so few. Transportation officials throughout the megaregion will have to balance priorities of inland side of transport networks with coastal access points.

[183] (OA US EPA, n.d.-d)
[184] (National Centers for Environmental Information, n.d.-a)
[185] (OA US EPA, 2016)
[186] Google maps was used to measure the distance between St. Petersburg and Titusville.
[187] (OA US EPA, n.d.-d)
[188] (National Centers for Environmental Information, n.d.-a)
[189] (National Centers for Environmental Information, n.d.-a)

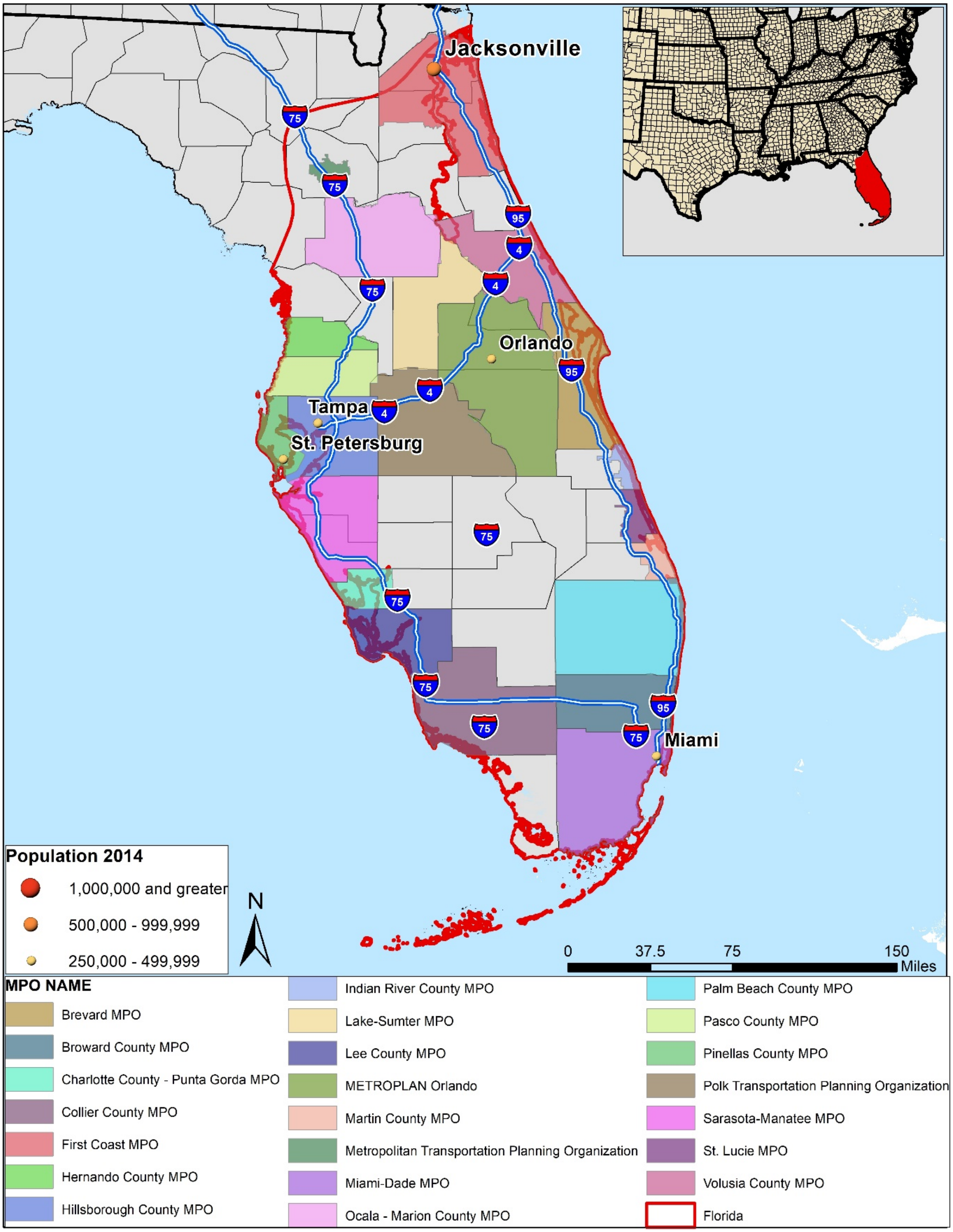

Figure 42: Southern Florida Megaregion reference map.

SOUTHERN FLORIDA

Principal Cities
1. Miami
2. Orlando
3. Tampa
4. Jacksonville

Transportation Governance Structures
Number of State Organizations: 2
MPOs: 22
Counties: 42

Population Information
2000 Population: 14.6M
2010 Population: 17.3M
Projected 2050 Population: 31.1M
Percent of U.S. GDP (2005): 5%
Percent of U.S. Population (2010): 6%

Most Common Natural Disaster Threats
Wildfire, floods, hurricanes, heat waves, tornados.

MPO and State DOT involvement with USDOT Resilience Grants:

Agency: Hillsboro MPO and South Florida MPOs
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: The Hillsboro MPO conducted a pilot program to identify vulnerabilities within the transportation system to flooding, storm surge, and sea level rise. The group documented risks so that potential mitigation strategies could be integrated into ongoing capital renewal programs for roadway rehabilitation.[190] Broward MPO, in partnership with the Miami-Dade MPO, Palm Beach MPO, and Monroe County Planning and Environmental Resources Department, also conducted a vulnerability assessment of transport infrastructure. The priority for this highly vulnerable region was to focus on identifying segments of rail and roadways that were regionally significant and particularly vulnerable to sea level rise, flooding and storm surge. The study included strategies for how agencies could integrate the findings into actions in regular decision-making processes in routine operations and maintenance decisions.[191]

Agency: Hillsboro MPO
Grant: Resilience and Durability to Extreme Weather (2018–2020)
Outcomes: The Hillsboro MPO and Pinellas County MPO, Pasco County MPO, and the Tampa Bay Regional Planning Council evaluated the vulnerability of transport infrastructure in the Tampa Bay Region to flooding and inundation. Results of this work will be integrated into regional long-range transportation plans as well as future hazard mitigation plans at the county and state levels.[192]

---

190 (FHWA, Hillsborough County MPO, n.d.)
191 (FHWA, Broward MPO, Miami-Dade MPO, Palm Beach MPO, Monroe County Planning and Environmental Resources Department, n.d.)
192 (“2018—2020/2024 Pilot Program: Resilience and Durability to Extreme Weather—Pilots—Resilience—Sustainability—Environment—FHWA,” n.d.)

5.11 Texas Triangle

The Texas Triangle (**Figure 43**) is vulnerable to a variety of climate changes and extreme weather events. The megaregion encompasses communities in central Texas most vulnerable to drought, flash flooding, and wildfire risks; the coastal communities tend to be more vulnerable to storm surge and sea level rise. As hurricanes and tropical storms continue to intensify, storm surges will become higher, and coastal infrastructure and communities will flood more frequently.[193] In 2016, an EPA report acknowledged that "Many cities, roads, railways, ports, airports and oil and gas facilities along the Gulf Coast are vulnerable to the combined impacts of storms and sea level rise. People may move from vulnerable coastal communities and stress the infrastructure of the communities that receive them."[194] Over time, Texas communities may see an uptick in inland migration, as residents search for less climate vulnerable communities. This will inevitably stress the transport systems that facilitate movement between regions, as well as more local infrastructure that support existing residents. Increased number of hot days will affect ground-level ozone and ultimately increase chances of respiratory disease throughout the state. Inland communities will continue to battle with flash flooding from rain events, in addition to expanding deserts from drier conditions and increased wildfire events.

Much of the state of Texas is experiencing a drought that started in October 2010. High temperatures in the summer has led to decreasing water levels in rivers and lakes.[195] While Texans are no strangers to hot and dry days, conditions continue to become more severe and carry the potential to have dramatic economic consequences to Texas ranchers and farmers. In 2005, 77% of the state's hay crop for cattle had been lost due to drought. Among the issues that droughts intensify, drought provide fuel for wildfires. In September 2011, Bastrop County, located in the center of the Texas Triangle Megaregion, suffered a wildfire that destroyed 34,000 acres and over 1,300 homes.[196] In a 2016 assessment, the U.S. Office of Cyber and Infrastructure Analysis identified transportation systems among the sectors most vulnerable to wildfires events.[197]

---

193 (U.S. EPA, 2016)
194 (U.S. EPA, 2016)
195 ("Everything You Need to Know About the Texas Drought," n.d.)
196 ("Everything You Need to Know About the Texas Drought," n.d.)
197 (National Department of Homeland Security, 2016)

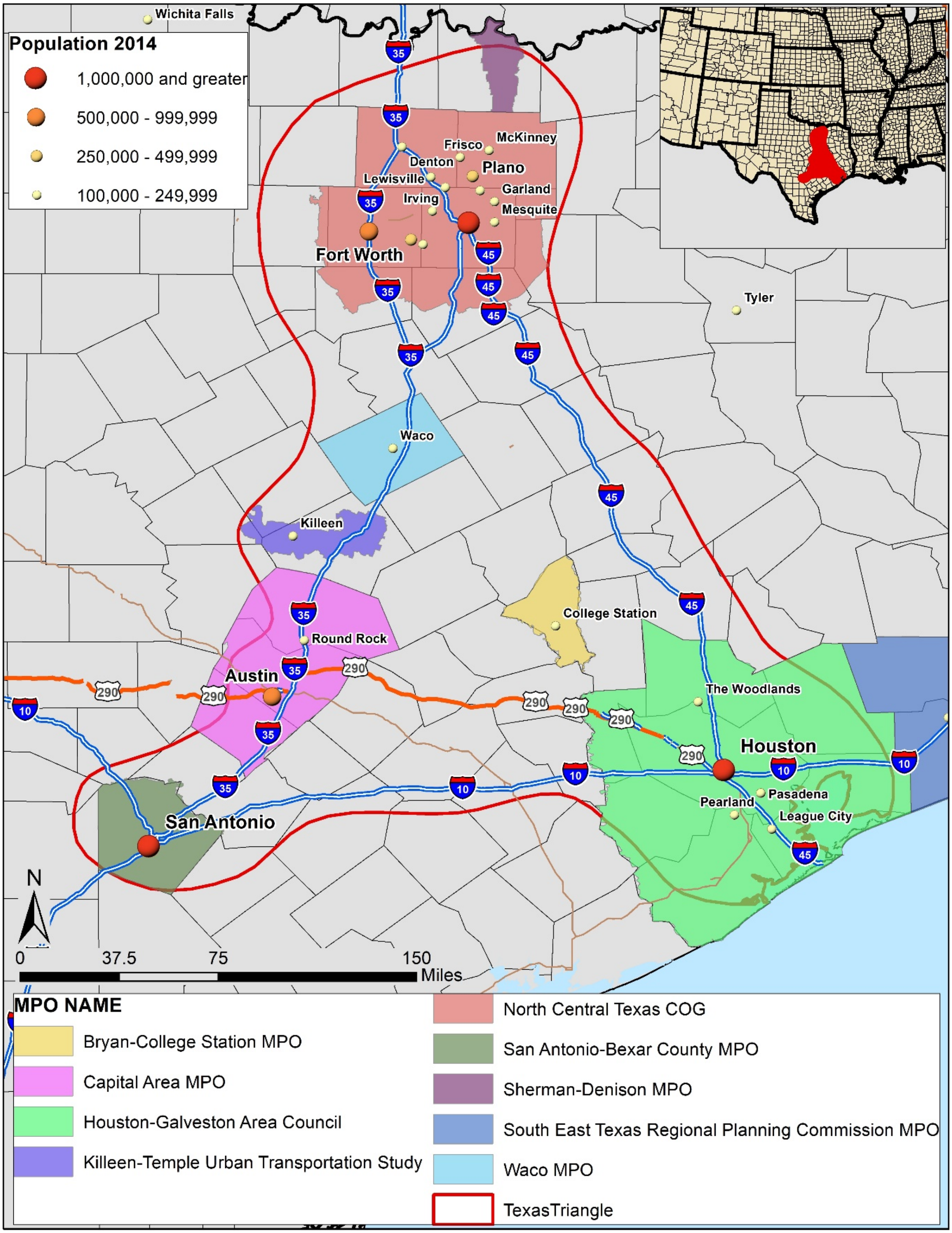

Figure 43: Texas Triangle Megaregion reference map.

TEXAS TRIANGLE

Principal Cities
1. Houston
2. Dallas-Fort Worth
3. Austin
4. San Antonio

Transport Governance Structures
Number of State Organizations: 1
MPOs: 8
Counties: 101

Population Information
2000 Population: 16M
2010 Population: 19.7M
Projected 2050 Population: 38.1M
Percent of U.S. GDP (2005): 7%
Percent of U.S. Population (2010): 6%

Most Common Natural Disaster Threats
Wildfires, tornado, heat wave, flooding, hurricane.

MPO AND STATE DOT INVOLVEMENT WITH USDOT RESILIENCE GRANTS:

Agency: Capital Area MPO (CAMPO) & North Central Texas Council of Governments (NCTCOG)
Grant: Vulnerability Assessments and Adaptation Options (2013–2015)
Outcomes: CAMPO partnered with the City of Austin Office of Sustainability to conduct a vulnerability assessment of the regional transportation system to extreme weather events, including flooding, drought, wildfires, and extreme hot and cold temperatures. This effort was a catalyst for a regional resilience working group in the region, and also led to improvements included in CAMPO's 2040 long-range transportation plan.[198] In anticipation of population growth and more demand on the regional transportation system, NCTCOG partnered with the City of Dallas, Fort Worth Transportation Authority, and the University of Texas at Arlington to determine how projected extreme weather events will affect transport infrastructure. Disruptions from historical extreme weather events have proved the dramatic impact that extreme weather events can have on the transport system. The study evaluated nineteen airports, roads, and passenger rail assets, and focused on impacts of extreme heat, flooding and rain events, drought, and the urban heat island effect. Results of this project would be integrated into project development and future regional plan prioritization criteria.[199]

Agency: Houston-Galveston Area Council (H-GAC)
Grant: Resilience and Durability to Extreme Weather (2018–2020)
Outcomes: In partnership with TxDOT, Harris County, and other local governments, H-GAC is identifying opportunities to integrate research and results of vulnerability and risk studies into the 2045 regional transportation plan and a panel group that considers future environmental effects. Part of this project includes opportunities to disseminate tools to local and county agency partners for informed future decisions.[200]

[198] (U.S. DOT, n.d.-a)
[199] (U.S. DOT, n.d.-b)
[200] (U.S. DOT, n.d.-d)

Chapter 6. Conclusion

The research team found that viewing resilience to natural disasters from the megaregional perspective is a useful scale to consider how populations and jobs may move between the metro areas that anchor a megaregion over the next several decades. This scale of analysis accounts for impacts to places in between major metro areas that may be dramatically impacted by a loss or gain in either population or employment, and which tend to be left out of regional-level analyses. The questions listed in the introduction are re-evaluated below for consideration of conclusions and recommendations.

How is economic impact typically measured post-disaster? How is the cost of transportation infrastructure evaluated?

We discovered multiple methodologies for estimating economic impact and found limited information specific to the economic impact on transportation agencies or transport infrastructure. The National Hurricane Center develops summary report for each tropical cyclone and hurricane event, which typically includes a summary multiple sources of economic impact estimates. The insurance industry employs its own method for developing an impact estimate. Transport agencies may provide economic impact estimates based on the number of days infrastructure was inoperable and unable to facilitate the flow of goods or people. Alternatively, a transport agency might record the amount of funding spent on repairing infrastructure damages stemming from a storm event. However, we were unable to find information at this level of detail.

What are the primary risks that each of the 11 U.S. megaregions face, and how do those risks vary by megaregion in terms of transport planning?

While each megaregion is vulnerable to different natural disasters, the geography and size of megaregions makes them inclusive of diverse natural disaster threats. Particularly with respect to changing weather patterns, megaregions are increasingly faced with challenges from both ends of the climate threat spectrum. Ultimately, transport agencies must evaluate the megaregion based on existing vulnerabilities and identify a strategy or plan to minimize risk and vulnerabilities within the system. MPOs and state DOTs have taken an active role in facilitating the conversation on transport resilience at a regional level and between regions.

Are there spatial patterns that can be observed in terms of demographic changes after a natural disaster? Is there any pattern in how population disperses within a certain range away from the area of impact, and do those people subsequently return to the city they were forced to leave?

Because areas within megaregions tend to be linked economically and through infrastructure systems, much more research is warranted at this scale to develop a deeper understanding for how people move within the megaregion as a result of natural disaster events, and how the demographic makeup of individual counties and regions changes in the aftermath of natural disaster events. Other aspects to consider are the shape and location of each megaregion. For example, the Gulf Coast Megaregion involves mostly coastal communities. This makes the entire megaregion both more susceptible to natural disaster events and more likely to lose population from migration after a disaster event (from residents moving further inland). The Texas Triangle, on the other hand, easily facilitates the movement of people from one metropolitan area to another—for example, from Houston to Dallas. Future research should take a focused look at migration patterns in all three megaregions (Texas Triangle, Gulf Coast, and Southern Florida) and evaluate changes in demographic characteristics and personal income of regions after natural disaster events. Future projects could also explore the factors that contribute to some counties recovering faster than others. What elements can counties or regions consider in the future to become more resilient to natural disasters?

As noted, as TSU researchers work on identifying the needs of vulnerable communities within a megaregion, they are creating a rubric-style decision-making matrix for transportation investments in a megaregion.[201] After natural disaster events, vulnerable populations are at increased risk prior to the natural disaster due to a lack of transportation options, financial ability, and other factors. Post-disaster, these communities face difficulties to return to pre-disaster conditions due to the quality of land infrastructure, lack of resources, job access opportunities, ability to reassemble the community, and the provision of mobility options that are readily accessible by different vulnerable stakeholders. Data and metrics on where vulnerable populations evacuate to and from could provide important data on the provision of mobility options. Metrics could identify pre-disaster conditions for the purpose of evaluation, and subsequently measure how many residents

[201]TSU's study: https://sites.utexas.edu/cm2/files/2019/03/Lewis_VulnCom_ExecutiveSummary.pdf

successfully integrate back into a community, find economic opportunities, and are able to access health and educational resources. It could also contribute more nuance to the conversation regarding what demographics of people are able to return to communities within a given timeframe after a disaster event.

Do MPOs have a vested interest in the recovery or resilience of MPOs in typically vulnerable areas?

We believe that MPOs do have a vested interest in the recovery or resilience of MPOs within the same megaregion that may be in more typically vulnerable areas to disaster events. While major megaregional projects are generally few and far between, we were excited to discover the number of inter-jurisdictional coordination efforts for natural disaster resilience and climate adaptation. The number of federally funded pilot projects spearheaded in partnership by state and MPO agencies provides support for Seltzer and Carbonell's theory. Agencies have reached beyond their jurisdictional requirements to tackle a challenge with wider ranging impacts, such as climate-related threats.

As coastal communities grapple with decisions to migrate inland or to other cities, MPOs will be at the focal point of this conversation, whether the migration occurs within one state or between two states. Additional research should be conducted to determine where vulnerable communities may be most likely to move, because an unexpected influx will stress existing transportation systems in those communities. Aside from direct impact to transport systems, MPOs have the ability to elevate the importance of resilience planning within planning principles that influence long-term plan project prioritization. MPOs can also serve as convening body within and between regions, and can come together to facilitate the conversation between other MPOs in a megaregion and county or state officials regarding resilience planning. Federal funding for MPOs could be used to fund regionally significant projects that contribute the most to regional resilience and help to alleviate pressure from already financially strapped local and state transportation budgets.

Finally, from a transportation perspective, an analysis of the impacts to infrastructure from natural disasters needs to be undertaken at a megaregional scale. As the level of impact of shadow evacuations on the transportation network during natural disaster emergency evacuations is being measured and assessed, measurement of congestion and mobility impacts within and throughout the megaregion due to population changes should be assessed. In addition, post-disaster impacts in terms of construction, maintenance, and additional infrastructure requirements should be added into the evaluation process of determining resiliency. As an example, the Houston area has been continuously impacted by heavy rainfall following a natural disaster, and while the base numbers of population and employment would indicate resiliency, resiliency in the ability of transportation funding to shift scarce dollars to this region is not evaluated within any metrics. Nor is the cost considered for MPOs, cities, and counties who often have to shift resources to fund rehabilitation and rebuilding of structures into their short- and medium-term planning documents, which places other projects further down the line to receiving funding.

This topic should continue to be studied and dissected to determine how places within a megaregion can become more resilient, and subsequently how resilience can contribute to strengthening the economic competitiveness of megaregions across the nation.

References

2018—2020/2024 Pilot Program: Resilience and Durability to Extreme Weather—Pilots—Resilience—Sustainability—Environment—FHWA. (n.d.). Retrieved November 26, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/extweatherpilot.cfm

About SACOG. (n.d.). Retrieved November 26, 2019, from Sacramento Area Council of Governments website: https://www.sacog.org/about-sacog

Amadeo, K. (2019, June 25). How Florence, Harvey, Maria, and Other Hurricanes Battered the Economy. Retrieved November 25, 2019, from The Balance website: https://www.thebalance.com/hurricane-damage-economic-costs-4150369

April U. (2018, September 21). The Impact of Hurricanes of the Transportation Industry- Penn Lease. Retrieved November 25, 2019, from Penn Intermodal Leasing, Inc website: https://www.pennlease.com/blog/impact-hurricanes-logistics-transportation-industry/

Armando Carbonell. (2011). *Regional Planning in America* (Ethan Seltzer, Ed.). Retrieved from www.lincolninst.edu/sites/default/files/pubfiles/regional-planning-in-america-chp.pdf

Beven, J. (2005, November 22). *Tropical Cyclone Report, Hurricane Dennis*. Retrieved from https://www.nhc.noaa.gov/data/tcr/AL042005_Dennis.pdf

Blake, E. S., Landsea, C. W., & Gibney, E. J. (2011). *NOAA Technical Memorandum NWS NHC-6* (p. 49).

Bureau of Transportation Statistics. (n.d.). Retrieved November 26, 2019, from U.S. Department of Transportation website: https://www.bts.gov/

California Energy Commission, & University of California, Berkeley. (2019). Exploring California's Climate Change Research. Retrieved from Cal-Adapt website: https://cal-adapt.org/

Cann, O. (2017, September 27). What exactly is economic competitiveness? Retrieved May 16, 2019, from World Economic Forum website: https://www.weforum.org/agenda/2017/09/what-is-economic-competitiveness/

Cities—United Nations Sustainable Development Action 2015. (n.d.). Retrieved November 25, 2019, from Sustainable Development Goals website: https://www.un.org/sustainabledevelopment/cities/

City of Houston. (2018). *Hurricane Harvey Recovery: A Progress Report*. Retrieved from City of Houston website: http://www.houstontx.gov/postharvey/public/documents/11.28.2018_progress_report.pdf

Columbia University. (2019). US Natural Hazards Index. Retrieved May 19, 2019, from National Center for Disaster Preparedness | NCDP website: https://ncdp.columbia.edu/library/mapsmapping-projects/us-natural-hazards-index/

Committee on Increasing National Resilience to Hazards and Disasters. (2012). *Disaster Resilience: A National Imperative*. Retrieved from https://www.nap.edu/catalog/13457/disaster-resilience-a-national-imperative

Congress of the United States Congressional Budget Office. (2016). *Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget* (p. 38). Retrieved from http://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf

Cornwall, W. (2014, July 24). Causes of Deadly Washington Mudslide Revealed in Scientific Report. Retrieved from National Geographic website: https://www.nationalgeographic.com/news/2014/7/140722-oso-washington-mudslide-science-logging/

Everything You Need to Know About the Texas Drought. (n.d.). Retrieved November 26, 2019, from StateImpact Texas website: http://stateimpact.npr.org/texas/topic/drought/

Executive Orders. (2016, August 15). Retrieved November 26, 2019, from National Archives website: https://www.archives.gov/federal-register/codification/executive-order/12148.html

Federal Emergency Management Agency. (2019a, June 3). About the Agency | FEMA.gov. Retrieved November 26, 2019, from About the Agency website: https://www.fema.gov/about-agency

Federal Emergency Management Agency. (2019b, August 6). Hazus | FEMA.gov. Retrieved November 26, 2019, from https://www.fema.gov/HAZUS

Federal Emergency Management Agency. (2019c, October 22). Community Resilience Indicators and National-Level Measures: A Draft Interagency Concept | FEMA.gov. Retrieved November 26, 2019, from https://www.fema.gov/community-resilience-indicators

Federal Funding Resources [Text]. (2012, March 1). Retrieved November 25, 2019, from US Department of Transportation website: https://www.transportation.gov/highlights/disaster-recovery/funding/federal

Federal Highway Administration. (n.d.-a). Fixing America's Surfact Transportation Act. Retrieved from FAST Act website: https://www.fhwa.dot.gov/fastact/

Federal Highway Administration. (n.d.-b). Fixing America's Surfact Transportation Act: Metropolitan Planning. Retrieved from FAST Act website: https://www.fhwa.dot.gov/fastact/factsheets/metropolitanplanningfs.cfm

Federal Highway Administration. (n.d.-c). Fixing America's Surfact Transportation Act: Statewide and Nonmetropolitan Planning. Retrieved from FAST Act website: https://www.fhwa.dot.gov/fastact/factsheets/statewideplanningfs.cfm

Federal Highway Administration. (n.d.-d). Gulf Coast Study: Phase 2, Task 4. Retrieved from FHWA Office of Planning, Environment and Realty, Sustainability. website: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_task4/index.cfm

FEMA. (2018, October 5). Disaster Recovery Reform Act of 2018 Transforms Field of Emergency Management | FEMA.gov. Retrieved November 25, 2019, from FEMA News Release website: https://www.fema.gov/news-release/2018/10/05/disaster-recovery-reform-act-2018-transforms-field-emergency-management

FHWA. (n.d.-a). Arizona—2013–2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from 2013–2015 Pilots website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/arizona/

FHWA. (n.d.-b). Colorado—TEACR - Ongoing And Current Research—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from U.S. Department of Transportation FHWA, Sustainability website: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/colorado/

FHWA. (n.d.-c). Land Use Scenario Planning—Publications—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from U.S. Department of Transportation FHWA, Sustainability website: https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/scenario/

FHWA. (n.d.-d). Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from U.S. Department of Transportation FHWA, Sustainability: Resilience Pilots website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/

FHWA. (n.d.-e). What Are—Megaregions—Planning—FHWA. Retrieved November 25, 2019, from U.S. Department of Transportation FHWA, Office of Planning, Environment, & Realty website: https://www.fhwa.dot.gov/planning/megaregions/what_are/

FHWA, Broward MPO, Miami-Dade MPO, Palm Beach MPO, Monroe County Planning and Environmental Resources Department. (n.d.). South Florida—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 26, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/south_florida/

FHWA, CDOT. (n.d.). Connecticut—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from FHWA Climate Resilience Pilot Program: Connecticut Department of Transportation website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/connecticut/

FHWA, DelDOT. (n.d.). Coastal Green Infrastructure to Enhance Resilience of State Route 1, Delaware—Green Infrastructure—Ongoing And Current Research—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from U.S. Department of Transportation FHWA, Sustainability, Green Infrastructure website: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/delaware/

FHWA, Hillsborough County MPO. (n.d.). Hillsborough MPO - 2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 26, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/florida/

FHWA, MaineDOT. (n.d.). Maine—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from FHWA Climate Resilience Pilot Program: Maine Department of Transportation website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maine/

FHWA, MaineDOT, New Hampshire DOT. (n.d.). Northeastern—Green Infrastructure—Ongoing And Current Research—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from U.S. Department of Transportation FHWA, Sustainability, Green Infrastructure website: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/northeastern/#toc502301476

FHWA, MassDOT. (n.d.). MassDOT - 2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from FHWA Climate Resilience Pilot Program: Massachusetts Department of Transportation website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/massdot/

FHWA, MSHA. (n.d.). Maryland—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from FHWA Climate Resilience Pilot Program: Maryland State Highway Administration website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maryland/

FHWA, MTC. (n.d.). Metropolitan Transportation Commission—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 26, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/mtc/

FHWA, MTC. (n.d.). Metropolitan Transportation Commission—MTC - Case Studies—Resilience—Sustainability—Environment—FHWA. Retrieved November 26, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/case_studies/san_francisco_mtc/

FHWA, NJTPA. (n.d.). New Jersey—Case Studies—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from Case Studies: North Jersey Transportation Authority—NJTPA website: https://www.fhwa.dot.gov/environment/sustainability/resilience/case_studies/new_jersey/

FHWA, NYSDOT. (n.d.). New York—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from FHWA Climate Resilience Pilot Program: New York State Department of Transportation website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/new_york/

FHWA, ODOT. (n.d.). Green Infrastructure Techniques for Resilience of the Oregon Coast Highway—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/oregon/

FHWA Road Management Operations. (n.d.-a). Hurricanes—FHWA Road Weather Management. Retrieved November 25, 2019, from Hurricanes website: https://ops.fhwa.dot.gov/weather/weather_events/hurricanes.htm

FHWA Road Management Operations. (n.d.-b). Rain & Flooding—FHWA Road Weather Management. Retrieved November 25, 2019, from Rain and Flooding website: https://ops.fhwa.dot.gov/weather/weather_events/rain_flooding.htm

FHWA, TDOT. (n.d.). Tennessee—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 26, 2019, from FHWA Climate Resilience Pilot Program: Tennessee Department of

Transportation website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/tennessee/

FHWA, WSDOT. (n.d.-a). Washington State—Case Studies—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/case_studies/washington_state/

FHWA, WSDOT. (n.d.-b). Washington—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/washington/

Fletcher, D. R., & Ekern, D. S. (2016). *Understanding Transportation Resilience: A 2016-2018 Roadmap*. Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-59(14)C_UnderstandingTransportationResilience-Roadmap.pdf

FWHA, MDOT. (n.d.). Michigan—2013-2015 Pilots—Pilots—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from U.S. Department of Transportation FHWA, Sustainability website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/michigan/

FWHA, VDOT. (n.d.). Hampton Roads—Case Studies—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from Case Studies: Hampton Roads, Virginia Department of Transportation—VDOT website: https://www.fhwa.dot.gov/environment/sustainability/resilience/case_studies/hampton_roads/

Georgia Disaster History. (n.d.). Retrieved November 26, 2019, from Georgia Emergency Management and Homeland Security Agency website: https://gema.georgia.gov/georgia-disaster-history

Grenzeback, L. (n.d.). *Case Study of the Transportation Sector's Response to and Recovery from Hurricanes Katrina and Rita*. 44. Retrieved from http://onlinepubs.trb.org/onlinepubs/sr/sr290grenzenbacklukmann.pdf

Hamel, L., Wu, B., Brodie, M., Sim, S.-C., & Marks, E. (2017). *An Early Assessment of Hurricane Harvey's Impact on Vulnerable Texans in the Gulf Coast Region*. Retrieved from http://www.houstontx.gov/postharvey/public/documents/12.2017_ehf_kff_harvey_survey.pdf

Ho, E., & Hastak, M. (n.d.). *Impact Analysis of Natural Calamities on Infrastructure and Industries*. 14. Retrieved from https://www.irbnet.de/daten/iconda/CIB11539.pdf

Holsinger, H. (2018, September). *Integrating Resilience into Transportation Planning*. Presented at the San Antonio, Texas. Retrieved from http://www.ampo.org/wp-content/uploads/2018/11/Holsinger-FHWA-Resilience-Overview-AMPO-9-28-2018.pdf

Holthaus, E. (2014, March 24). Climate Change May Make Terrible Mudslides More Common. Retrieved November 25, 2019, from Slate Magazine website: https://slate.com/technology/2014/03/oso-wash-mudslide-climate-change-may-bring-more-such-disasters.html

How Climate Change Is Affecting California. (2018, March 21). Retrieved November 26, 2019, from Climate Reality website: https://www.climaterealityproject.org/blog/how-climate-change-affecting-california

Hurricane Andrew, 25 Years Later—Federal Reserve Bank of Atlanta. (2017, August 24). Retrieved November 25, 2019, from Regional Economics website: https://www.frbatlanta.org/economy-matters/regional-economics/2017/08/24/hurricane-andrew-25-years-later

Hurricanes: Science and Society: 2005- Hurricane Rita. (n.d.). Retrieved November 25, 2019, from 2005—Hurricane Rita website: http://www.hurricanescience.org/history/storms/2000s/rita/

Ii, J. L. B. (2014). *Tropical Cyclone Report: Hurricane Frances* (p. 30). Retrieved from National Hurricane Center website: https://www.nhc.noaa.gov/data/tcr/AL062004_Frances.pdf

Irfan, U. (2019, June 11). The severe floods soaking the Midwest and Southeast are not letting up. Retrieved November 25, 2019, from Vox website: https://www.vox.com/2019/6/11/18659676/flood-midwest-nebraska-iowa-forecast

Karagyozov, K., Razmov, T., Todorova, M., Varadinova, J., & Dzhaleva-Chonkova, A. (2012). *Todor Kableshkov University of Transport, Sofia* (p. 75). Todor Kableshkov University of Transport, Sofia.

Knabb, R. D., Rhome, J. R., & Brown, D. P. (2005, December 20). *Tropical Cyclone Report, Hurricane Katrina*. Retrieved from https://www.nhc.noaa.gov/data/tcr/AL122005_Katrina.pdf

Lawrence, M. B., & Cobb, H. D. (2005). *Tropical Cyclone Report: Hurricane Jeanne* (p. 20). Retrieved from National Hurricane Center website: https://www.nhc.noaa.gov/data/tcr/AL112004_Jeanne.pdf

Leach, P. T. (2012, November 9). NY-NJ Port Assesses Damage From Sandy. Retrieved November 25, 2019, from JOC website: /port-news/us-ports/port-new-york-new-jersey/ny-nj-port-assesses-damage-sandy_20121109.html, https://www.joc.com/port-news/us-ports/port-new-york-new-jersey/ny-nj-port-assesses-damage-sandy_20121109.html

Legislative Budget Board. (2018). *Hurricane Harvey's Fiscal Impact on State Agencies*. Retrieved from State of Texas website: https://www.lbb.state.tx.us/Documents/Publications/Presentation/5443_SFC_.pdf

Levin, M. (2015, September 22). How Hurricane Rita anxiety led to the worst gridlock in Houston history. Retrieved November 25, 2019, from Houston Chronicle website: https://www.chron.com/news/houston-texas/houston/article/Hurricane-Rita-anxiety-leads-to-hellish-fatal-6521994.php

Lewis, Dr. C. (2018). *Creating a Framework to Determine Purpose and Need for Increased Travel Options in the Megaregion for Vulnerable Communities*. Retrieved from Texas Southern University website: https://sites.utexas.edu/cm2/files/2019/03/Lewis_VulnCom_ExecutiveSummary.pdf

Mayfield, M. (2006). Tropical Cyclone Report. *National Hurricane Center*, 33.

Meko, T. (2019, April 25). Mapping America's wicked weather and deadly disasters. [The Washington Post]. Retrieved November 25, 2019, from https://www.washingtonpost.com/graphics/2019/national/mapping-disasters/?noredirect=on

Murray, J. (2019, March 13). Colorado weather: Bomb cyclone brings big impact as blizzard whips state. Retrieved November 25, 2019, from The Denver Post website: https://www.denverpost.com/2019/03/13/colorado-weather-bomb-cyclone-blizzard/

National Centers for Environmental Information. (2019). Billion-Dollar Weather and Climate Disasters. Retrieved from NOAA website: https://www.ncdc.noaa.gov/billions/

National Centers for Environmental Information. (n.d.-a). Billion-Dollar Weather and Climate Events in the U.S.: 1980-2017. Retrieved from NOAA website: https://www.ncdc.noaa.gov/billions/events/US/1980-2017

National Centers for Environmental Information. (n.d.-b). Calcuations: Billion-Dollar Weather and Climate Disaster. Retrieved from NOAA website: https://www.ncdc.noaa.gov/monitoring-references/dyk/billions-calculations

National Department of Homeland Security. (2016, April). U.S. Critical Infrastructure 2025: A Strategic Risk Assessment. Retrieved November 26, 2019, from National Department of Homeland Security website: https://info.publicintelligence.net/DHS-OCIA-CriticalInfrastructure2025.pdf

National Hurricane Center. (2019, May 3). Saffir-Simpson Hurricane Wind Scale. Retrieved May 3, 2019, from National Hurricane Center, NOAA website: https://www.nhc.noaa.gov/aboutsshws.php

National Hurricane Center. (n.d.). NHC Data Archive. Retrieved November 26, 2019, from https://www.nhc.noaa.gov/data/#tracks_all

NOAA, National Hurricane Center and Central Pacific Hurricane Center. (n.d.). Hurricanes in History. Retrieved November 25, 2019, from Hurricanes in History website: https://www.nhc.noaa.gov/outreach/history/

NOAA, National Weather Service. (n.d.). Hurricane Matthew in the Carolinas: October 8, 2016. Retrieved November 26, 2019, from National Weather Service website: https://www.weather.gov/ilm/Matthew

O'Brien, B., & Szekely, P. (400AD, 39:55). New Mexico, Colorado Wildfires Force Hundreds To Evacuate. Retrieved November 25, 2019, from HuffPost website: https://www.huffpost.com/entry/colorado-new-mexico-wildfires-ute-park_n_5b12efa6e4b0d5e89e2024ee

Oliva, S., & Lazzeretti, L. (2018). Measuring the economic resilience of natural disasters: An analysis of major earthquakes in Japan. *City, Culture and Society*, *15*, 53–59. https://doi.org/10.1016/j.ccs.2018.05.005

Pant, R., Barker, K., & Zobel, C. W. (2014). Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors. *Reliability Engineering & System Safety*, *125*, 92–102. https://doi.org/10.1016/j.ress.2013.09.007

Pasch, R. J., Brown, D. P., & Blake, E. S. (2004). *Tropical Cyclone Report: Hurricane Charley*. Retrieved from https://www.nhc.noaa.gov/data/tcr/AL032004_Charley.pdf

Press Release – U.S. Transportation Secretary Elaine L. Chao Announces $157 Million in Infrastructure Grants to 34 Airports in 19 States and One Territory [Template]. (2019, September 30). Retrieved November 26, 2019, from Federal Aviation Administration website: https://www.faa.gov/news/press_releases/news_story.cfm?newsId=24276

Regional Plan Association. (2016). Our Maps—America 2050. Retrieved May 3, 2019, from http://www.america2050.org/maps/

Regional Plan Association. (n.d.). Megaregions—America 2050. Retrieved November 25, 2019, from American 2050 website: http://www.america2050.org/content/megaregions.html#more

Rodrigue, J.-P., Comtois, C., & Slack, B. (2017). *The geography of transport systems* (4th edition). London ; New York: Routledge, Taylor & Francis Group.

Southern California Association of Governments. (2012). *Regional Transportation Plan 2012-2035: Sustainable Communities Strategy Towards a Sustainable Future*. Retrieved from Southern Calirofnia Association of Governments website: http://rtpscs.scag.ca.gov/Documents/2012/final/f2012RTPSCS.pdf

Stewart, S. R. (2006, February 14). *Tropical Cyclone Report Hurricane Cindy*. Retrieved from https://www.nhc.noaa.gov/data/tcr/AL032005_Cindy.pdf

Times-Picayune, B. E., NOLA com |. The. (n.d.). Louisiana to lose a seat in Congress. Retrieved November 25, 2019, from NOLA.com website: https://www.nola.com/news/politics/article_59064a55-5c8c-551b-bcf0-1b242223ecc7.html

Tools—Resilience—Sustainability—Environment—FHWA. (n.d.). Retrieved November 26, 2019, from U.S. Department of Transportation FHWA, Sustainability website: https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/

UN Habitat. (2019, February). Resilience. Retrieved from UN Habitat For a Better Urban Future website: https://unhabitat.org/resilience/

United Nations. (n.d.). Climate Adaptation. Retrieved from UN Environment Programme website: https://www.unenvironment.org/explore-topics/climate-change/what-we-do/climate-adaptation

United Nations. (n.d.). Mitigation. Retrieved from UN Environment Programme website: https://www.unenvironment.org/explore-topics/climate-change/what-we-do/mitigation

U.S. Department of Transportation. (n.d.). State and Local Funding Resources. Retrieved from Transportation.gov website: https://www.transportation.gov/highlights/disaster-recovery/funding/state-local

U.S. DOT. (n.d.-a). FHWA Climate Resilience Pilot Program: Capital Area Metropolitan Planning Organization (CAMPO). Retrieved from U.S. Department of Transportation FHWA website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/campo/

U.S. DOT. (n.d.-b). FHWA Climate Resilience Pilot Program: North Central Texas Council of Governments. Retrieved from U.S. Department of Transportation FHWA website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/nctcog/

U.S. DOT. (n.d.-c). Gulf Coast Study—Ongoing And Current Research—Resilience—Sustainability—Environment—FHWA. Retrieved November 25, 2019, from Gulf Coast Study website: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/

U.S. DOT. (n.d.-d). Resilience Pilots. Retrieved from U.S. Department of Transportation FHWA, Sustainability website: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/

U.S. EPA. (2016, August). *What Climate Change Means for Texas*. Retrieved from https://archive.epa.gov/epa/sites/production/files/2016-09/documents/climate-change-tx.pdf

US EPA, OA. (2013, January 18). About EPA [Collections and Lists]. Retrieved November 26, 2019, from US EPA website: https://www.epa.gov/aboutepa

US EPA, OA. (2016, May 23). Climate Impacts on Coastal Areas [Overviews and Factsheets]. Retrieved November 26, 2019, from US EPA website: https://www.epa.gov/climateimpacts/climate-impacts-coastal-areas

US EPA, OA. (2019, July 10). Regional Resilience Toolkit [Reports and Assessments]. Retrieved November 26, 2019, from US EPA website: https://www.epa.gov/smartgrowth/regional-resilience-toolkit

US EPA, OA. (n.d.-a). Climate Impacts in the Midwest [Overviews and Factsheets]. Retrieved November 25, 2019, from /climate-impacts/climate-impacts-midwest

US EPA, OA. (n.d.-b). Climate Impacts in the Northeast [Overviews and Factsheets]. Retrieved November 25, 2019, from Climate Change Impacts website: /climate-impacts/climate-impacts-northeast

US EPA, OA. (n.d.-c). Climate Impacts in the Northwest [Overviews and Factsheets]. Retrieved November 25, 2019, from /climate-impacts/climate-impacts-northwest

US EPA, OA. (n.d.-d). Climate Impacts in the Southeast [Overviews and Factsheets]. Retrieved November 26, 2019, from Climate Change Impacts website: /climate-impacts/climate-impacts-southeast

US EPA, OA. (n.d.-e). Climate Impacts in the Southwest [Overviews and Factsheets]. Retrieved November 25, 2019, from /climate-impacts/climate-impacts-southwest

US EPA, OA. (n.d.-f). Climate Impacts on Transportation [Overviews and Factsheets]. Retrieved November 25, 2019, from Climate Change Impacts website: /climate-impacts/climate-impacts-transportation

US EPA, OEI. (2016, November 8). Environmental Topics [Collections and Lists]. Retrieved November 26, 2019, from US EPA website: https://www.epa.gov/environmental-topics

U.S. Global Change Research Program. (n.d.). Southwest | Global Climate Change Impacts in the United States 2009 Report Legacy site. Retrieved November 25, 2019, from https://nca2009.globalchange.gov/southwest/index.html#Landscape_Transformation

Welcome to Stats & Events. (n.d.). Retrieved November 26, 2019, from California Department of Forestry & Fire Protection website: https://www.fire.ca.gov/stats-events/

Wolshon, B., Herrera, N., Parr, S., & Zhang, Z. (2018). *The Effect of Shadow Evacuation in Megaregion Disasters: A Pilot Study* (p. 24). Retrieved from https://sites.utexas.edu/cm2/files/2018/09/Year-1-WolshonEtAL_The-Effect-of-Shadow-Evacuation-in-Megaregion-Disasters-A-Pilot-Study.pdf

Wootson Jr, C. R. (2018, November 26). The deadliest, most destructive wildfire in California's history has finally been contained. Retrieved November 26, 2019, from Washington Post website: https://www.washingtonpost.com/nation/2018/11/25/camp-fire-deadliest-wildfire-californias-history-has-been-contained/

World Economic Forum. (n.d.-a). Chapter 3: Regional Analysis and Selected Economy Highlights. Retrieved May 16, 2019, from Global Competitiveness Index 2017-2018 website: http://wef.ch/2ffDWiM

World Economic Forum. (n.d.-b). Global Competitiveness Index 2017 2018. Retrieved May 16, 2019, from Global Competitiveness Index 2017-2018 website: http://wef.ch/2wa0AjJ

Yarnell Hill Fire Report Released. (2013, December 1). Retrieved November 25, 2019, from Fire Rescue Magazine website: https://firerescuemagazine.firefighternation.com/2013/12/01/yarnell-hill-fire-report-released/