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The vulnerability of the U.S. food system to climate change

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Introduction

Over the last century, the United States food system has evolved to rely on large-scale, vertically integrated systems to produce, process, and deliver food and other agricultural products to consumers in the U.S. and beyond. The success of the U.S. food system has been achieved through a focus on land- and labor-efficient production of commodities in a national system characterized by monocultures, geographic specialization and increasing concentration and consolidation in all phases of the food system. For example, since 2000, oligopolies (the control of at least 50% of the market by 4 firms) have emerged in the agricultural input (Fuglie et al. 2012), grain distribution and food processing (CorpWatch 2014) and grocery retailing (Food and Water Watch 2010) sectors of the U.S. food system. In 2007, just 2 percent of U.S. farms and ranches accounted for more than 50 percent of all U.S. agricultural sales and from 60 to 70 percent of the sales of high value crops (vegetables, fruits, nuts, nursery and greenhouse products), hogs, dairy, poultry and beef (Hoppe and Banker 2010).

The 21st century challenges of climate change and resource scarcity bring a new urgency to concerns about the sustainability of the U.S. food system (National Research Council 2010). The energy intensity and natural resource impacts associated with industrial production practices, coupled with the geographic specialization and concentration of the U.S. food system, reduce the nation's capacity to mitigate and adapt to climate change. In addition, the interactions between energy, water and land use in the U.S. are likely to amplify climate change effects (Hibbard and Wilson 2014).

This paper provides a literature review of the climate change vulnerability and resilience of food systems. To explore the vulnerability of the U.S. food supply to climate change, the concept of climate vulnerability and its relationship to resilience is explained, the geography of the U.S. food supply is described and a regional climate history of the U.S. is presented. A discussion of U.S. producer perceptions of climate change provides evidence of the unique place-based vulnerability created by the interaction of regional climate effects and the geographic specialization of U.S. food production. Because the U.S. food system has global reach, this paper concludes with an assessment of the climate change vulnerability of domestic as well as global food production, processing, and distribution systems.

Understanding climate vulnerability

The vulnerability of a system is a function of the exposure and the sensitivity of the system to hazardous conditions mediated by the ability of the system to cope, adapt, or recover from the effects of those conditions, i.e., the adaptive capacity or resilience of the system (Smit and Wandel 2006). Climate vulnerability is a characteristic of human and natural systems, is dynamic and multi-dimensional, and is influenced by complex interactions among social, economic, and environmental factors (Adger et al. 2007). Because agricultural systems are human-dominated ecosystems, the vulnerability of agriculture and food systems to climate change is strongly dependent not just on the biophysical effects of climate change but also on the actions taken by humans to moderate those effects through adaptive responses (Marshall 2010).

Adaptive actions are shaped by the operating context within which decision-making occurs (for example, the context created by the quality and availability of natural, human, social, financial and physical capital, social norms, non-climate stressors, and government policy and programs), access to effective adaptation options, and the individual capability to take adaptive action. The adaptive capacity of a system moderates the potential impact of climate change to the system through actions that serve to protect the system from damaging climate effects, to recover from damages or to achieve a transformation to a new more climate resilient system.

The potential impact of climate change is a function of exposure of the system to specific climate effects, such as drought, heatwave, or flooding, and the sensitivity of the system to those effects (Lengnick 2015). For example, annual crop production situated in a flood plain is more sensitive to flooding than some perennial crops such as pecans or hay. Tree fruit production systems are more sensitive to late spring freezes than diversified vegetable production systems.

In the context of climate change adaptation, resilience is defined as “the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change” (Parry et al. 2007). Resilient systems exhibit three key behaviors associated with high adaptive capacity: response capacity — the ability to respond quickly and effectively to buffer disturbances; recovery capacity — the ability to quickly restore the existing system after damage; and transformation capacity — the ability to transition the system to a new identity when desired or necessary (Walker and Salt 2012). A resilient system has high adaptive capacity and a system with high adaptive capacity is resilient.

The vulnerability of a system is a function of potential impact and the adaptive capacity of the system. For example, beef production in a confined animal feeding operation (CAFO) is more vulnerable to a disruption in power supplies than a pasture-based beef production system because CAFO requires power to provide cattle water and feed. In contrast, pasture-based systems can be managed to provide multiple feed and water sources that cattle can be moved to as desired. Pasture-based systems can also provide many other ecosystem-based climate protection services such as temperature moderation and protection from high winds, heavy rainfall and flooding (Lengnick 2015).

Climate change exposure, sensitivity and adaptive capacity are determined by local conditions. Exposures vary widely across the U.S., as do sensitivities, which are determined by the specific responses of production, manufacturing and distribution systems to local climate exposures. Adaptive capacity is also placed-based and is a function of the response, recovery and transformation capacity of the food system within the local operating context. A better understanding of the interactions between the geography of the U.S. food supply and regional patterns of climate change exposures in the U.S. offers an opportunity to explore the climate change vulnerability of the U.S. food supply.

The geography of the U.S. food supply

America's plate is filled to overflowing with industrial food produced at home and sourced from around the world.[1] California leads the nation in food production and processing, but specific areas within the Pacific Northwest, the Midwest, the Great Plains, the Midwest and the Southeast contribute significant volumes of just one or two kinds of products to the U.S. food supply (See Table 1). Imports, primarily from Mexico, Canada, Chile and other countries in Central America and Asia, fill seasonal gaps in domestic production (e.g., fresh vegetables in winter) or provide a type or quality of product not produced domestically (e.g., tropical fruits year around). Trade in food and other agricultural products has been important to America since colonial times, but the global movement of food, particularly perishable produce, has increased dramatically since the early 1980s, when the necessary technology and transportation systems were developed (Halweil 2002). The acceleration of corporate concentration in the food industry and the commodification of food have accompanied these dramatic changes in global food flows (Lyson 2006).

Fruits and vegetables

California has long been the nation's leading producer of fruits, nuts and vegetables. The Central Valley's Mediterranean climate, ideal for crop production as long as there is sufficient water for irrigation, has supported an incredibly diverse and productive agricultural industry that produces about 90 percent of all nuts, 70 percent of all processed vegetables, and 50 percent of all fresh vegetables grown in the U.S. each year. Other leading fresh vegetable producing states are Florida, Arizona, Georgia and Washington, together with California accounting for about 75 percent of U.S. domestic fresh vegetable production in 2012. About 25 percent of the vegetables consumed in the U.S. are imported, mostly from Mexico and Canada.

Together, three Pacific states — California, Washington and Oregon — produce much of the U.S.-grown fruit supply: virtually all of the apricots, avocados, nectarines, pears, boysenberries and raspberries, more than 95 percent of the nation's strawberries and sweet cherries, more than 75 percent of the apples, prunes and plums, 70 percent of the peaches and nearly half of all U.S.-grown blueberries. Imports contribute almost 50 percent of the U.S. consumption of fresh fruits, with Mexico, Chile and Costa Rica the major suppliers (Huang 2013).

Grains and beans

[1] All information on specific crops and livestock production reported in this section were obtained from the Agricultural Marketing Resource Center at agmrc.org unless otherwise noted. Production statistics included in this section were calculated using data from U.S. Department of Agriculture Annual Production Summaries for 2012 unless otherwise noted.

Wheat is the principal food grain produced in the U.S. and is the third-largest grain crop by value, behind corn and soybeans (Wheat Overview 2013). Different types of wheat are grown in different regions of the U.S. Bread wheat (hard wheat) accounts for almost 70% of total U.S. wheat production and is grown in the Great Plains. Kansas, Oklahoma and Texas together account for about 75 percent of total U.S. production of bread wheat in 2012. Wheat used for cakes and cookies (soft wheat) accounts for about 20% of total U.S. wheat production and is produced east of the Mississippi River. The white wheat used to make pasta and cereal makes up the remainder of the U.S. total and is grown in the Pacific Northwest, Montana and North Dakota. The U.S. is a major supplier of wheat and wheat products to global markets and has held the largest share in global trade for many decades. About half of the U.S. wheat crop is exported each year.

The production of corn and soybeans, the nation's top two grain crops by value, is centered in the Midwest. Although only two percent of the corn produced in the U.S. is directly eaten by people. Corn is an important livestock feed and is also processed into a multitude of food and industrial products including starch, sweeteners, corn oil, beverage and industrial alcohol and fuel ethanol. In 2012, about 8 percent of U.S. corn production was exported, mostly for use as livestock feed. Soybeans are crushed to produce soybean meal and soybean oil. The meal is used as livestock feed while soybean oil is used for human consumption, accounting for more than half of all the vegetable oil consumed in the U.S. (Soystats 2012). The U.S. is the world's largest exporter of soybeans and about half of the U.S. grown supply is exported each year.

U.S. rice production accounts for less than 2 percent of the world total, but it is important in global trade because most rice is consumed where it is produced. In recent years, about half of U.S. production has been exported. Arkansas is the nation's leading producer of rice, accounting for about 50% of U.S. production and together with Louisiana, Mississippi, Missouri and Texas, produced almost 80% of U.S. rice production in 2012.

Dry edible beans are produced in the Pacific Northwest and the Northern Great Plains. Pinto, navy, black, garbanzo and red kidney are the principal dry beans produced in the U.S. with North Dakota leading the nation in production for more than 20 years. In 2012, North Dakota, Idaho and Washington produced more than 50% of the total U.S. production of dry edible beans.

Meat, seafood and dairy

America's beef production is centered in the south central Great Plains. This region is home to three of the top five calf-producing states and processes about 70 percent of all U.S.-grown beef. Although beef calves are produced on farms and ranches throughout the U.S., most spend the last months of their lives in feedlots in Texas, Nebraska and Kansas, which together produce nearly 60 percent of the nation's beef supply. About 12 percent of the U.S. beef supply is imported as meat and livestock to assure a continuous supply of fresh beef throughout the year. Canadian imports of both live cattle and beef contribute to the total U.S. supply of grainfed cattle. Mexico supplies cattle to U.S. feeding operations during seasonal lows in domestic calf production.

U.S. pork production is centered in the Midwest, which is home to nine of the top ten hog-producing states that together, over the last decade, have consistently produced about 70 percent of total U.S. annual pork production. Iowa is the hog-producing capital of the nation, producing about a quarter of the country's pork each year. The U.S. is the largest exporter of pork and pork products globally, with exports averaging 20 percent of commercial pork production over the last decade (USDA-FAS 2014).

American poultry production is centered in the Southeast. Georgia is the nation's leading producer of chickens and along with Arkansas, Alabama, North Carolina, Mississippi and Texas produces about two-thirds of the nation's supply. The U.S. is the world's largest turkey producer and exporter of turkey products. Turkey production is centered in the Midwest and the Southeast, with each region accounting for about 40% of national production in 2012. The U.S. is the world's largest producer and second largest exporter of poultry meat, exporting about 20 percent of U.S. chicken meat and 14 percent of turkey in 2012.

The per capita consumption of seafood in the U.S. is much lower than other animal proteins, but still adds up to nearly five billion pounds each year (Fish Watch 2013). More than 90% of the U.S. seafood supply is imported. About half the seafood consumed in the U.S. is wild-caught, and the other half is farmed. In 2011, seafood from Asia accounted for the majority of U.S. imports, but Chile, the European Union and Canada also contribute significantly to the U.S. seafood supply.

The U.S. is the single largest producer of cow's milk in the world. About half of the milk supply is processed into cheese, another third into fluid milk and cream products and the remainder into dairy products such as butter, ice cream and milk powders. California and Wisconsin have led the nation in dairy production since the 1980's. For the last decade, they have together produced about one-third and one-half of the national supply of milk and cheese, respectively. Milk and dairy product imports to the U.S. are dominated by specialty cheese imports from Europe and milk powder from New Zealand. About 13 percent of the U.S. milk supply was exported in 2012.

The industrial development of the U.S. food system since the mid-1900s has created a food supply geography characterized by extreme regional specialization and concentration that, for many food types, just a few states dominate national production. This geographic specialization in food production creates the potential for widespread climate change impacts to the U.S. food supply, particularly if the food production systems in a region have low adaptive capacity or are especially sensitive to the climate change exposures characteristic of that region (See Table 1).

The geography of climate change

The U.S. Global Change Research Program (USGCRP) released the Third National Climate Assessment (NCA) in May 2014 (National Climate Assessment 2014). The NCA provides a detailed regional analysis of climatic changes and associated impacts in the U.S. over the last century and scenario-based projections through the end of this century. Observed changes over the last century include increasing average temperatures and weather variability, warmer nights and winters, a lengthening of the growing season and an increase in the frequency and intensity of extreme weather events.[2]

Although these trends hold true for most of the U.S., the degree of change is quite different depending on location. Climate change has not and will not be experienced the same way throughout the U.S., because regional topography interacts with the global climate system to create regional patterns of climate change effects. These observed changes in regional climate are projected to increase in pace and intensity through the end of this century unless there is a substantial reduction in global emissions of heat-trapping gases.

The climate record shows that average temperatures in the U.S. have increased over the last century (Figure 1). More warming has occurred in the western and northern regions of the country than in the Southeast; however, starting about 1980, all regions of the country began warming and the first decade of the twenty-first century was warmer than any previous decade in every region. These warming trends are apparent in climate data relevant to agricultural production. The growing season lengthened during the twentieth century, increasing by about nineteen days in the West, ten days in the North and six days in the Southeast (Figure 2) and minimum temperatures increased faster than maximum temperatures, leading to more rapid warming at night and in winter (EPA 2014). These kinds of changes in daily and seasonal temperature patterns have the potential to disrupt agricultural production because of the sensitivity of crops, livestock and pests to seasonal temperature patterns and temperature extremes (Walthall et al. 2012).

Average precipitation increased during the twentieth century, although this increase is partly the result of two major droughts in the first half of the century (in 1930 and 1960). Figure 3 illustrates the changes in average precipitation across the U.S. through the twentieth century. While average U.S. precipitation was higher than the baseline over the last forty years, the patterns of change in average precipitation are not as clear as those for temperature. Significant regional patterns of change are more clearly illustrated by observed increases in very heavy precipitation in the Midwest and Northeast and associated changes in flood magnitude trends (Figures 4 and 5).

Over the next few decades, the entire U.S. is projected to continue to warm by about 2 to 4 degrees Fahrenheit. This rate of warming represents a rate of change higher than that observed

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[2] All of the observed and projected weather data discussed in this section is from Our Changing Climate (Walsh et al. 2014), unless otherwise noted.

in the last few decades. Current trends in weather variability and extremes are projected to increase in frequency and intensity through mid-century, as the pace of climate change continues to accelerate. More frequent, intense and longer lasting droughts and heatwaves in the Southwest (Garfin et al. 2014) will increase weather-related disruptions to the U.S. supply of domestically produced fruits, vegetables, dairy and beef. Warmer winters, increases in high temperature extremes and more frequent drought and heatwaves in the Great Plains will reduce domestic production of wheat and livestock (Ojima et al. 2014). In the Midwest, average temperature increases, wetter springs, and a greater chance of heatwave during pollination and drought during grain fill will reduce corn and soybean yields (Prior et al. 2014). Increasing temperatures, more frequent and intense heatwaves, and sea level rise are expected to reduce crop and livestock yields in the Southeast (Carter et al. 2014). Throughout the country, more hot nights will lower the yield and quality of grain, fruit and fiber crops and reduce meat, milk and egg production (Hatfield et al. 2014).

Projections of climate change effects on the U.S. food system beyond mid-century are less certain, because the rate of change is driven largely by the level of heat-trapping gases released to the atmosphere by human activities. Projections for the latter part of the twenty-first century suggest that average temperatures will rise about 4 degrees Fahrenheit if substantial reductions in emissions are achieved and by as much as 10 degrees Fahrenheit if current trends in emissions continue (Walsh et al. 2014). The pace and intensity of projected changes will depend on trends in global levels of heat-trapping gases in the atmosphere. Higher levels of heat-trapping gases will drive more rapid and intense changes in weather variability and extremes.

Heat waves are projected to increase throughout most of the U.S. and droughts are likely to become more intense in the Southwest. The growing season will continue to lengthen by as much as a month in many parts of the nation and as much as two months in the west. The number of frost days will decline by twenty to thirty days in most of the nation and by even more in the west. Dry periods will lengthen, especially in the west, and hot nights are expected to increase by more than eighty per year across the southern U.S. by the end of the century. There will likely be more winter and spring precipitation in the northern parts of the U.S and less precipitation in the Southwest, while summer and fall precipitation is likely to remain about the same or decrease in most regions. Both the frequency and intensity of heavy rainfall events are projected to increase throughout the nation.

Climate risk, the novel risk associated with the increased weather variability and extremes accompanying climate change, is expected to become an increasingly important factor in agricultural production (Hatfield et al. 2014) and in other sectors of the food system (USDA 2013) as the pace and intensity of climate change accelerates through this century.

Voices from the field: climate risks to U.S. food production

The climate risk management experiences of agricultural producers offer a unique perspective on the place-based nature of climate change vulnerability in the U.S. food system. Recent research has documented the ability of rural people engaged in agriculture to detect changes in local climate, such as altered plant and animal phenology, new distributions of species, shorter or longer growing seasons and a shifting frequency of extreme weather events (Howe and Leiserowitz 2013). Although farmer perceptions of changes in weather variability and extremes have been researched in many other countries since about 2000, the climate change perceptions of U.S. producers have only recently begun to be documented (Walthall et al. 2012).

A large survey of industrial corn and soybean producers in the Midwest and Northern Great Plains regions found that 68% believed that the climate is changing (Arbuckle et al. 2013). The farmers in these regions reported that the greatest weather-related challenges to their production systems are longer dry periods, more frequent drought and heatwave, followed by increased pest and diseases and excessive rainfall. Almost 60 percent of the surveyed farmers believe that they should take steps to protect their land from increased weather variability.

A survey of more than 1000 commodity crop producers growing corn, cotton, grain sorghum, rice and wheat in Mississippi, Texas, North Carolina and Wisconsin found that 40 to 50 percent do not believe that climate change has been scientifically proven, while the remaining farmers split about evenly between those that do believe it has been proven and those having no opinion (Rejesus et al. 2013). This research found no geographic differences in farmer perceptions of climate change effects on agricultural production. Between 60 and 75 percent of respondents believe that normal weather cycles explain most or all of the recent changes in weather variability and extremes that they have perceived. The farmers surveyed in this study suggested that they would be most likely to diversify crops, buy crop insurance, modify lease arrangements or exit farming altogether if weather variability and extremes intensify in coming years.

About 150 Maine farmers representing seven major commodity groups - potato, dairy, blueberry, vegetable, apple, beef and nursery plants - participated in focus groups to discuss the future of agriculture in their state (Jemison et al. 2014). When asked about future challenges, only one farmer mentioned climate change and only a few farmers, primarily blueberry and apple growers, expressed concerns about changing environmental conditions; however, most of the participating farmers expressed concerns about new challenges associated with changing weather patterns such as more erratic weather, novel pests, and more extreme weather events. Farmers reported a variety of adaptive actions taken in response to these changes such as crop diversification, the addition of drainage or irrigation systems, season extension in protected growing conditions such as hoop houses, and the use of ecological production practices, such as enhancing soil quality, that are designed to buffer weather extremes.

Case study research of twenty-five award-winning U.S. farmers and ranchers managing sustainable[3] production systems throughout the country suggests that changing weather

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[3] The term sustainable agriculture was defined by the U.S. Congress in the 1990 Farm Bill as "an integrated system of plant and animal production practices having a site-specific application that will, over the long term: satisfy human food and fiber needs; enhance the environmental quality and the natural resource base upon which the agricultural economy depends; make the most

conditions have challenged crop and livestock productivity, processing and/or marketing practices since about 2000 (Lengnick 2015). These producers report that more variable weather, more frequent and intense weather extremes, increased competition for water supplies, longer growing seasons and novel pest pressures have required changes in their production practices to maintain productivity and profitability over the last 15 to 20 years. A kind of geography of climate vulnerability emerges in the specific details of adaptive responses to these weather-related challenges.

Producers in the Northwest report relatively moderate climate change effects over the last two decades, although warmer winters, a declining snow pack, and wetter springs and falls have complicated fruit and grain production in the region (Lengnick 2015). Kole Tonnemaker grows certified organic tree fruit, vegetables and hay on the 126 acre Tonnemaker Hill Farm in Royal City, WA. Kole hasn't seen much change in seasonal weather patterns over the 34 years he has managed the farm. Although access to water for irrigation has not been an issue in his region, reduced snow pack in recent years and projections that summer surface water flows will decrease through mid-century have Kole concerned about future water supplies for agriculture.

Russ Zenner has produced wheat, barley, and dry beans for more than 40 years on the 2800 acre Zenner Family Farms in Genesee ID. More rainfall in the spring and drier conditions in late summer and fall have complicated crop management in his dryland (non-irrigated) production system. Wetter spring conditions over the past few years have increased soil compaction problems and driven a dramatic increase in fungicide use by grain producers in his region. Russ believes that grain farmers need new knowledge and technologies, along with federally-subsidized crop insurance, to successfully manage increasing climate risk in the years ahead. He expressed concern that a lack of research and development in the U.S. on climate change adaptation in agriculture represents a significant barrier to cultivating a resilient U.S. food system.

Farmers and ranchers in the Southwest report increasing challenges associated extreme drought and heatwave, more intense competition for water supplies and more frequent heavy rains (Lengnick 2015). Paul Muller co-owns and operates Full Belly Farm, a 400-acre diversified organic farm producing more than 80 different crops including vegetables, herbs, nuts, flowers, fruits, grains and livestock in Guinda, CA. Although water conservation has always been focus of his farm management, weather changes in recent years – continuing drought coupled with dryer and warmer winters, longer and more variable spring and fall seasons, and more heavy rainfall - have required a switch to more drought tolerant cover crops, upgrades to a more water-efficient irrigation systems, and changes in the management of riparian

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efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; sustain the economic viability of farm operations; and enhance the quality of life for farmers and society as a whole." This definition explicitly acknowledges the multiple dimensions of sustainability — ecological, social and economic — and provides specific design criteria for sustainable agriculture systems.

areas on the farm to reduce the risk of flood damage to cropland. Paul expressed concern about the lack of coordinated planning for agricultural adaptation to climate change in his region and elsewhere.

Julia Davis Stafford is a 4th generation co-owner and operator of the 130,000 acre CS Ranch near Cimarron, NM. She has worked with her family to manage the ranch's cow-calf and stocker enterprises for more than 30 years. Extreme drought, more variable precipitation, reduced snowpack and more wind have caused increasing management challenges on the ranch and forced a gradual destocking from 3000 to about 800 head over the last 15 years. Julia is concerned that continued forced destocking because of drought will have widespread impacts on the livelihoods of ranch owners and employees as well as the local community.

Great Plains producers have been challenged by warmer temperatures, more extreme rainfall in the north, and more extreme drought throughout the region (Lengnick 2015). Gabe Brown has been producing cattle, feed and food grains for more than 30 years near Bismarck, North Dakota. Brown's Ranch produces livestock and a diversity of crops on 5,000 acres of native rangeland, perennial forages, and no-till cropland producing corn, wheat, oats, barley, sunflowers, rye and alfalfa. Since about 2007, Gabe has noticed weather extremes getting more frequent and flooding becoming the norm rather than just a rare event. More variable weather has increasingly interfered with crop production by altering seasonal patterns of conditions favorable for field work such as planting and harvesting. A popular speaker at farming conferences nationwide for many years, Gabe has noticed a growing interest among farmers in new practices to reduce climate risk in agricultural production.

Gary Price produces cattle on the restored the native grasslands that dominate the landscape of his 2500 acre 77 Ranch in Blooming Grove, Texas. Gary has noticed a number of changes in the weather, which used to be fairly predictable, over the 40 years he has been raising cattle in Blooming Grove. He used to plan cattle production to take advantage of reliably good grazing conditions from March to July and September to November, but these patterns have been disrupted by increasing variability in rainfall and more frequent and intense droughts and heatwaves over the last five years. In response, Gary has reduced the size of his cowherd to about eighty-five percent of maximum carrying capacity and he has leased additional rangeland as it becomes available near the ranch as insurance against declining forage yields in times of drought.

In the Midwest, rapid temperature swings, more variable rainfall, more very heavy downpours and catastrophic flooding have challenged producers (Lengnick 2015). Ron Rosmann produces certified organic corn, oats, soybeans, rye, and barley, plus pasture-based beef, pork and poultry on the 700 acre Rosmann Family Farms located near Harlan, Iowa. More variable weather and more heavy rainfalls, particularly in spring, have complicated grain production in the region by narrowing the time when conditions are favorable for fieldwork. As a result, Ron says that many conventional corn and soybean farmers in the region have abandoned best management practices in an effort to get field work done at all. Many farmers in the region are also upgrading and expanding tile drainage systems to better manage more frequent heavy rainfalls. Wetter spring weather, earlier spring warmup and a lengthening growing season have created new weed management challenges in grain crops and an increase in the frequency and intensity of weather extremes have required more careful livestock management, particularly in winter.

Farmers in the Northeast have been challenged by more variable weather, heatwaves, more heavy rainfall and extreme weather events, and an increase in livestock parasite pressures and plant diseases (Lengnick 2015). Jim Hayes has been raising pasture-based livestock at the 160 acre Sap Bush Hollow Farm located west of Albany, New York since 1979. More dry periods and drought, more frequent and stronger winds, and extreme weather over the last 15 years have challenged farm operations and required significant investment in new infrastructure on the farm. Jim has leased additional pastureland to increase forage reserves in case of drought, built additional ponds to increase water storage capacity on the farm, and upgraded portable poultry huts to withstand higher winds. More frequent and intense heavy rainfalls required the construction of a new drainage system to redirect increased surface runoff and a new barn with a raised concrete floor to provide dry shelter for livestock. Warmer winters and increased rainfall has increased parasite pressures in sheep. After experiencing the effects of widespread damage to road and power systems by back-to-back hurricanes Irene and Lee in the late summer of 2011, Jim added solar power backup systems and maintains a larger feed reserve.

Southeast region producers report increased challenges from more frequent drought and heatwave, increased pest populations, changes in pest behavior, novel pests, and more frequent and intense weather extremes (Lengnick 2015). Ken Dawson has managed a diversified organic production system since 1990 at Maple Spring Gardens located in Cedar Grove, North Carolina. Ken grows a highly diverse rotation of vegetables, cut flowers, and small fruits on 14 acres. Although southeast agricultural producers are used to highly variable weather, Ken believes that temperatures and precipitation have become more variable over his 40 years of farming in the region. The last normal year that he remembers on the farm was in 2001. Since then, Ken has experienced more variable spring temperatures, record wet and dry periods, record hot and cold periods, and record-breaking heatwaves in summer. Prior to 2010, he had never experienced temperature-related declines in fruit set, but heatwaves in 2010, 2011 and 2012 reduced tomato yields significantly. In response to these changes in weather variability, Ken has adjusted seasonal planting schedules and selected more heat-tolerant varieties in order to maintain continuous harvests of high quality fresh vegetables through the growing season.

Will Harris is the 4th generation to own and operate White Oak Pastures, a 2500 acre livestock farm located in southwest Georgia. Will produces and processes beef, pork, goat, poultry, lamb and rabbit in an integrated rain-fed, pasture-based system. Although temperatures have increased and precipitation seems to have grown more variable during Will’s more than 60 years on the farm, he has not made any changes in management practices to date. Other farmers in the region have responded to these weather changes by increasing their use of irrigation. If dry periods and droughts continue to intensify in coming years as projected, Will believes he will have to find a way to irrigate his pastures in a region marked by increasing competition for limited groundwater resources.

Although research documentation is sparse, there is some evidence that agricultural production systems in the U.S. are vulnerable to the increased weather variability and extreme weather events associated with climate change. Key exposures challenging producers in the Southwest and Southeast regions are increasing temperatures and continuing drought, while producers in the Midwest and Northeast are struggling to manage more frequent heavy rainfalls and narrowing windows when conditions are favorable for fieldwork. National case study research of farmers and ranchers producing vegetables, fruits and nuts, grains and livestock products with sustainable production practices found that producer perceptions of climate exposures on their farms are consistent with regional patterns of climate change effects; however, survey research of commodity crop producers in the Midwest and South found little evidence that geographic location influenced producer perceptions of climate change. The available research suggests that many U.S. producers are making changes in production practices to maintain productivity under current climate conditions and have thought about changes in production practices should climate change effects intensify through mid-century.

The vulnerability of the U.S. food system

The U.S. food system has proven remarkably resilient over the last hundred and fifty years, adapting to a diversity of production conditions across the nation to supply national and international markets. This resilience has been largely achieved through continuous public support of research and development to benefit industrial agriculture and food systems, significant financial subsidy in the form of direct payments, cost-share programs, subsidized crop insurance and disaster payments, and natural resource subsidies produced through the use of fossil fuels and the degradation of soil, water, air quality, biodiversity and community health and well-being (Francis et al. 2013). Paradoxically, this public support for the U.S. food system has, at the same time, eroded its resilience, because this support shelters the system from social and environmental disturbances (Berardi, Green and Hammon 2011).

Food systems are more vulnerable to global environmental changes when they have the following characteristics: a heavy reliance on external or distant resources; low diversity; inequitable access to resources; inflexible governance; highly specialized production, supply and marketing chains; and subsidies (both financial and technological) which mask environmental degradation (Ericksen 2008). These characteristics, widely recognized as critical challenges to the sustainability of the U.S. food system (National Research Council 2010), take on new importance as barriers to climate resilience.

In recent years, evidence that climate change effects are beginning to overwhelm the adaptive capacity of the U.S. food system is growing. For example, in 2010, drought and heatwave, punctuated by very heavy rainfalls set high temperature and rainfall records and caused localized agricultural losses from the Gulf coast through Ohio and the Northeast (National Climatic Data Center 2010). Hurricanes Irene and Lee hit the East Coast within one week of each other in the summer of 2011 to create the largest and most expensive natural disaster in New York state history (Stanne 2012). A late spring freeze following an unusually warm spring made 2012 the worst year ever recorded for Michigan fruit growers (Melker 2012), while 80 percent of agricultural land in the United States suffered drought conditions that year, resulting in a record high 14 billion dollars in crop insurance payments (Taxpayers 2013). U.S. beef prices rose to record highs in 2013 as a result of historic drought in Texas the previous year (Waters 2013). In spring 2014, for the first time in the state's history, California vegetable and fruit growers learn that they will get no water from federal or state water projects because of continuing extreme drought (Hurdle 2014). California's water crisis remained front-page news in spring 2015 as the first groundwater use laws in the state's history go into effect to address the increasingly unsustainable use of groundwater as a replacement for dwindling surface water supplies (Fitchette 2015).

Regional climate change exposures have the potential for widespread effects in the U.S. food system because of the geographic specialization and concentration of agricultural production and associated processing industries, as shown in Table 1. The largely irrigated systems of vegetable and fruit production that dominate much of the agriculture of the Pacific states are particularly sensitive to extreme drought conditions, exacerbated by increased competition for water from metropolitan areas and for natural resources and the unsustainable use of groundwater.

The CAFO production of cattle in the southern Great Plains is sensitive to increased temperatures, more frequent and intense heatwaves and drought, and increasing competition for dwindling surface and groundwater resources. Grain production in the Great Plains and the Midwest is sensitive to warmer winters, more variable springs, summer heatwave, drought and flooding and lower yields mean higher prices of an essential input to CAFOs. The CAFO production of poultry centered in the Southeast is sensitive to increasing summer temperatures, increased frequency and intensity of heatwaves and other extreme weather events, and increased competition for declining water resources in the region. Because virtually all pork and poultry production takes place in CAFOs, these production systems are also sensitive to disruptions in feed, water and power supplies – three critical resources subject to interactions that amplify climate change effects on the U.S. food supply (Hibbard and Wilson 2014).

The erosion of natural, human, social, financial, and physical resources that has accompanied the industrialization of the U.S. food system degrades regional adaptive capacity and reduces the resilience of the U.S. food supply (Lengnick 2015). Poor soil and water quality, unsustainable water consumption, and monocultures dependent on inputs of fertilizers and pesticides reduce the ecological response capacity U.S. agriculture. Social response capacity has been degraded by the low financial returns, transfer of wealth out of the local community, and negative impacts to individual and community well-being associated with U.S. agricultural production systems. The extreme specialization and concentration of the U.S. food system may greatly increase the risk of catastrophic failure in the face of disturbance because large, highly efficient networks generate positive feedbacks which eventually drive the system to self-destruct (Goerner, Lietaer and Ulanowicz 2009).

Because the U.S. food system is tightly connected to global markets, vulnerability of the U.S. food supply to climate change effects is a function of global resource availability and climate change impacts on production and distribution systems located elsewhere. Climate change is already disrupting the global food system and these disturbances are projected to increase in number and intensity in coming years (Expert Stakeholder Workshop 2013). Global operating conditions shaped by international agreements, policy and politics, social unrest and environmental changes are both affected by and influence U.S. food system conditions. New demands from a dynamic global economy, the continued decline in the quality and availability of natural resources, and the unprecedented challenges of climate change are just beginning to take their toll on the U.S. food system.

Production and consumption vulnerabilities to climate change have received the most attention by agricultural (e.g., Hatfield 2014) and food security researchers to date (eg., Eakin 2010), but climate change effects are already being felt throughout the world's food systems by businesses involved in the agricultural supply, processing, distribution and retailing sectors. Global food manufacturers and retailers report a variety of climate-related risks currently under active management, including increased variability in raw material supplies, lower quality and higher prices, increasing water scarcity, more disruptions and failures of distribution networks, increased incidence of work force disruption and changing consumer demand (Wong and Schuchard 2011). Global changes in ecosystem services, climate disruptions and food security in other countries will influence the price and availability of food to U.S. consumers (Expert Stakeholder Workshop 2013). The highly networked structure of the global food system also increases the risk of a disturbance cascading through the system with potentially widespread effects (Goerner, Lietaer and Ulanowicz 2009).

Conclusion

The U.S. food system has proven remarkably resilient over the last hundred and fifty years, but a synthesis of recent literature suggests that the geographic concentration and specialization of the system may be a key climate change vulnerability. Geographic specialization in food production creates the potential for widespread climate change impacts to the U.S. food supply, particularly if the production systems in a region have low adaptive capacity or are especially sensitive to the climate change exposures characteristic of that region.

Vegetable and fruit production in the Northwest and Southwest regions are particularly sensitive to reduced water supplies, warmer winters and more variable spring weather. Grain production in the Great Plains and the Midwest are sensitive to more variable weather, warmer winters, heatwave and hot summer nights and flooding caused by more frequent heavy rains. The concentration of beef, pork and poultry production in confined animal feeding operations located in the southern Great Plains and the Southeast are particularly sensitive to increased frequency and intensity of extreme weather and interruptions in feed, water and power supplies associated with interactions between land, water and energy use that amplify climate change effects.

Although evidence is sparse, it appears that more variable weather and more frequent and intense weather extremes associated with climate change are beginning to challenge the adaptive capacity of the U.S. food system. Farmers and ranchers in the U.S. report that increased weather variability and more frequent and intense weather extremes have increased the costs and complexity of food production. Global businesses operating in the U.S. agricultural input, processing, distribution and retailing sectors have begun to actively manage supply networks to reduce disruptions associated with climate change effects.

Food systems that rely on external or distant resources and specialized production, supply and marketing chains appear to be particularly vulnerable to global environmental change. The highly networked nature of the global food system further increases the risk of a disturbance in one region having widespread effects. These characteristics, widely recognized as critical challenges to the sustainability of the U.S. food system, take on new importance as barriers to climate resilience.

More empirical research is needed to understand and assess the sensitivity and adaptive capacity of the U.S. food system to climate change effects in the input, production, processing, and distribution sectors. What key sensitivities emerge through interactions between the U.S. food production geography and regional patterns of climate change? What kinds of adjustments are needed to reduce those sensitivities? How do we assess the adaptive capacity of the U.S. food system? What kinds of policies and programs are needed to enhance the adaptive capacity of the U.S. food system to climate change? Can the U.S. food system cultivate climate resilience while supplying abundant and healthful food to national and global markets? These are just a few key questions that must be explored if we are to sustain the U.S. food supply in a changing climate.

Table 1 A Geography of the Climate Vulnerability of the U.S. Food Supply. Geographic specialization in U.S. food production creates the potential for widespread climate change impacts to the U.S. food supply, particularly if the production systems in a region have sensitivities and/or a low adaptive capacity to the climate change exposures in that region

Fig. 1 Observed U.S. Temperature Change in the 20th Century. The map illustrates temperature changes over the past 22 years (1991 – 2012) compared to the 1901-1960 average. Every region has warmed except for a few locations in the Southeast and eastern Oklahoma. The bar graphs illustrate the average temperature changes by decade for 1901-2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph (2000s decade) includes 2011 and 2012. The period from 2001 to 2012 was warmer than any previous decade in every region (Walsh et al. 2014)

Fig. 2 Observed Changes in the Frost Free Season in the 20th Century. The frost-free season length, defined as the period between the last occurrence of 32 ^{o}F in the spring and the first occurrence of 32^{o}F in the fall, has increased in each U.S. region during 1991-2012 relative to 1901-1960. Increases in frost-free season length correspond to similar increases in growing season length (Walsh et al. 2014)

Fig. 3 Observed U.S. Precipitation Change in the 20th Century. The map illustrates annual total precipitation changes for 1991-2012 compared to the 1901 – 1960 average. Most areas, except for Arizona, the intermountain west and parts of the Southeast, have experienced wetter conditions. The bars on the graphs show average precipitation differences by decade for 1901 – 2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph is for 2001-2012 (Walsh et al. 2014).

Fig. 4 Observed Change in Very Heavy Precipitation Since 1958. The map shows percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region of the continental U.S. The changes shown in this figure are calculated from the beginning and end points of the trends for 1958 to 2012. These changes are larger than natural variations for the Northeast, Midwest, Southeast, Puerto Rico, the Great Plains and Alaska. (Walsh et al. 2014)

Fig. 5 Trends in Flood Magnitude in the 20th Century. Triangle color (green=increasing, brown=decreasing), size (magnitude) and orientation (pointing up=increasing trend, pointing down=decreasing trend) indicate direction and magnitude of change of annual flooding between the 1920's and 2008. Most significant are the increasing trends in the Midwest and Northeast and the decreasing trend in the Southwest (Walsh et al. 2014)

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Table 1 A Geography of the Climate Vulnerability of the U.S. Food Supply. Geographic specialization in U.S. food production creates the potential for widespread climate change impacts to the U.S. food supply, particularly if the production systems in a region have sensitivities and/or a low adaptive capacity to the climate change exposures in that region.

Region	Foods Produced	Key Climate Change Exposures[a]
Northwest	Fruits, potatoes, wheat, dry beans	Wetter springs and falls, warmer winters, declining snow pack, projected reduction in summer streamflow
Southwest	Fruits, nuts, vegetables, dairy	Extreme drought, more frequent/intense heatwave and heavy rain, more competition for water
Great Plains	Wheat, beef, dry beans	Increased temperatures, more frequent heavy rain, more extreme drought and heatwave
Midwest	Corn, soybeans, pork, dairy	More variable rainfall and temperatures, rapid temperature swings, more frequent heavy rain, catastrophic flooding
Northeast	Apples, milk	More variable rainfall and temperatures, more heatwave, more frequent heavy rain and extreme events, increase in plant disease
Southeast	Rice, poultry	More frequent drought and heatwave, increased pest populations, changes in pest behavior and novel pests, more frequent and intense weather extremes, more competition for water
Imports[b]	Vegetables - Mexico and Chile Fruits – Mexico, Chile and Costa Rica Seafood[c] – Asia, Chile, European Union, Canada	Mexico – increases in temperature, reduction in precipitation, increased frequency and intensity of extreme weather Chile – increases in weather variability, lengthening growing season, increases in temperatures, reduction in precipitation Costa Rica – increases in temperatures and reduction in precipitation

a. Key climate change exposures reported by U.S. farmers and ranchers using sustainable agriculture practices (Lengnick 2015), except import exposures (World Bank 2009). b. Principle suppliers of imported fruits, vegetables and seafood which contribute to 50%, 25% and 90% of U.S. domestic consumption, respectively. c. A number of climate-related threats to both capture fisheries and aquaculture have been identified including ocean warming and acidification, changes in inland precipitation and water management and increased frequency and intensity of extreme weather events (Brander 2007).

Figure 1

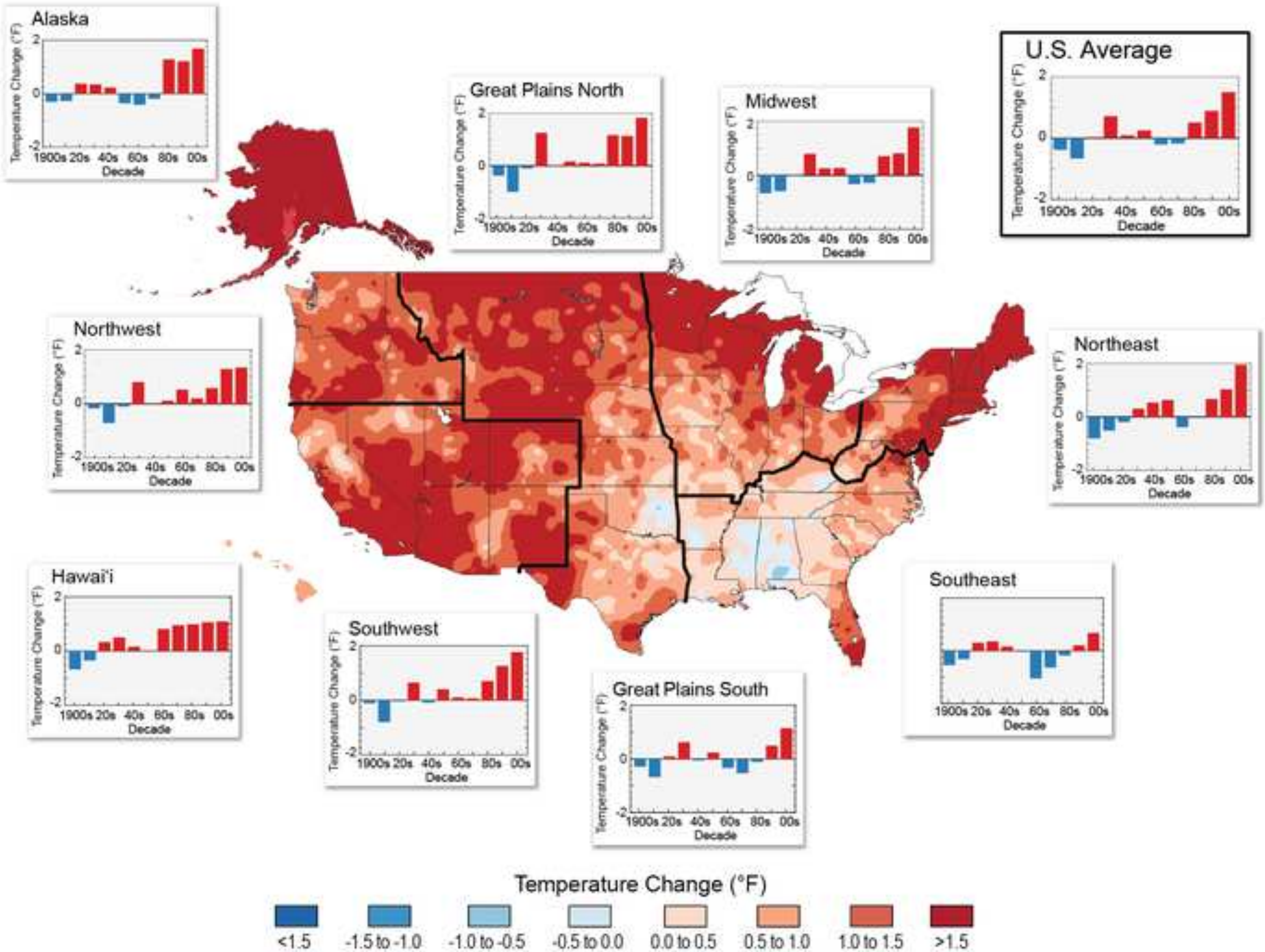

Alaska
Great Plains North
Midwest
U.S. Average
Northwest
Northeast
Hawai'i
Southwest
Southeast
Great Plains South
Temperature Change (°F)
Decade
1900s 20s 40s 60s 80s 00s
<1.5
-1.5 to -1.0
-1.0 to -0.5
-0.5 to 0.0
0.0 to 0.5
0.5 to 1.0
1.0 to 1.5
>1.5

Figure 2

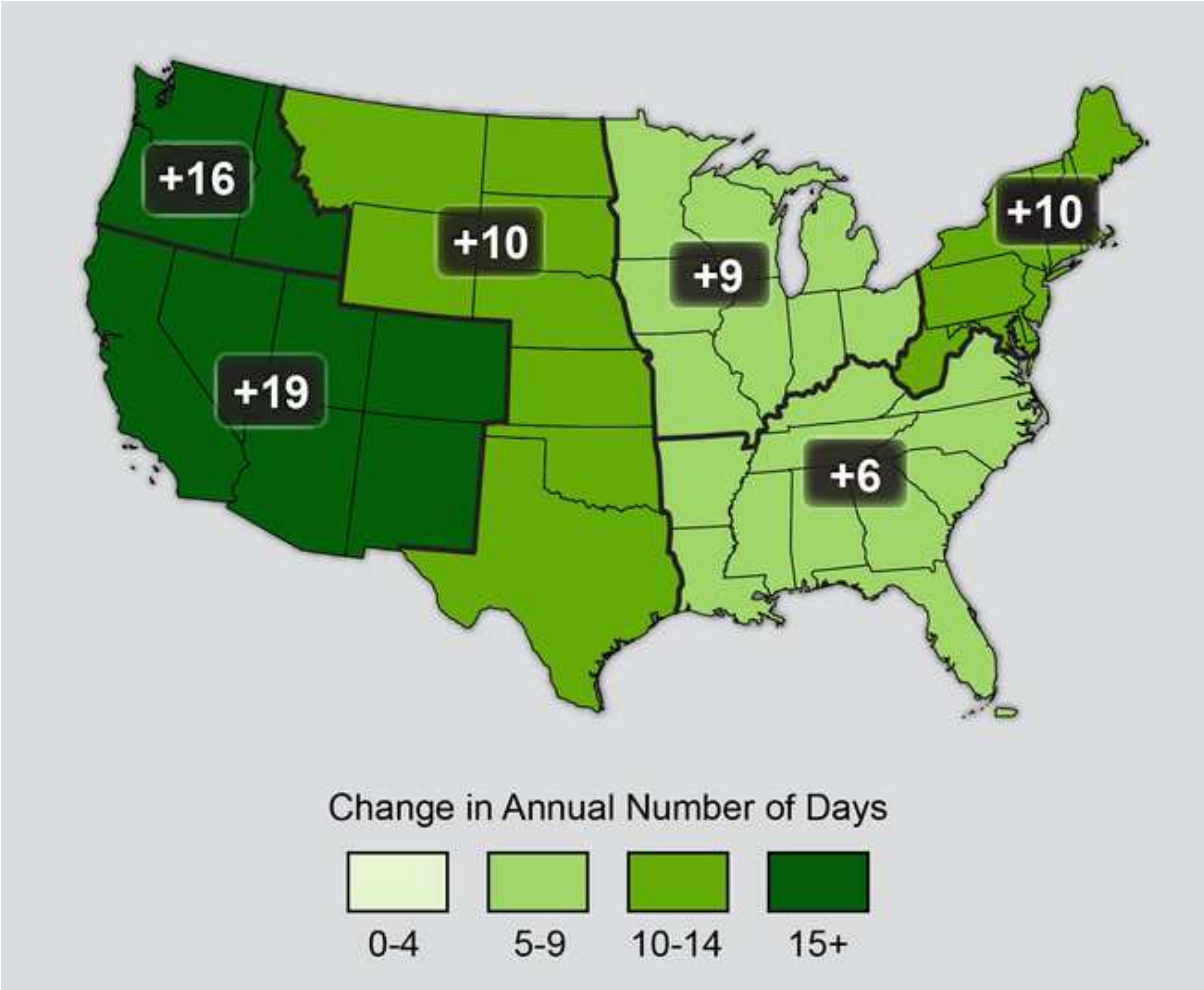


Figure 3

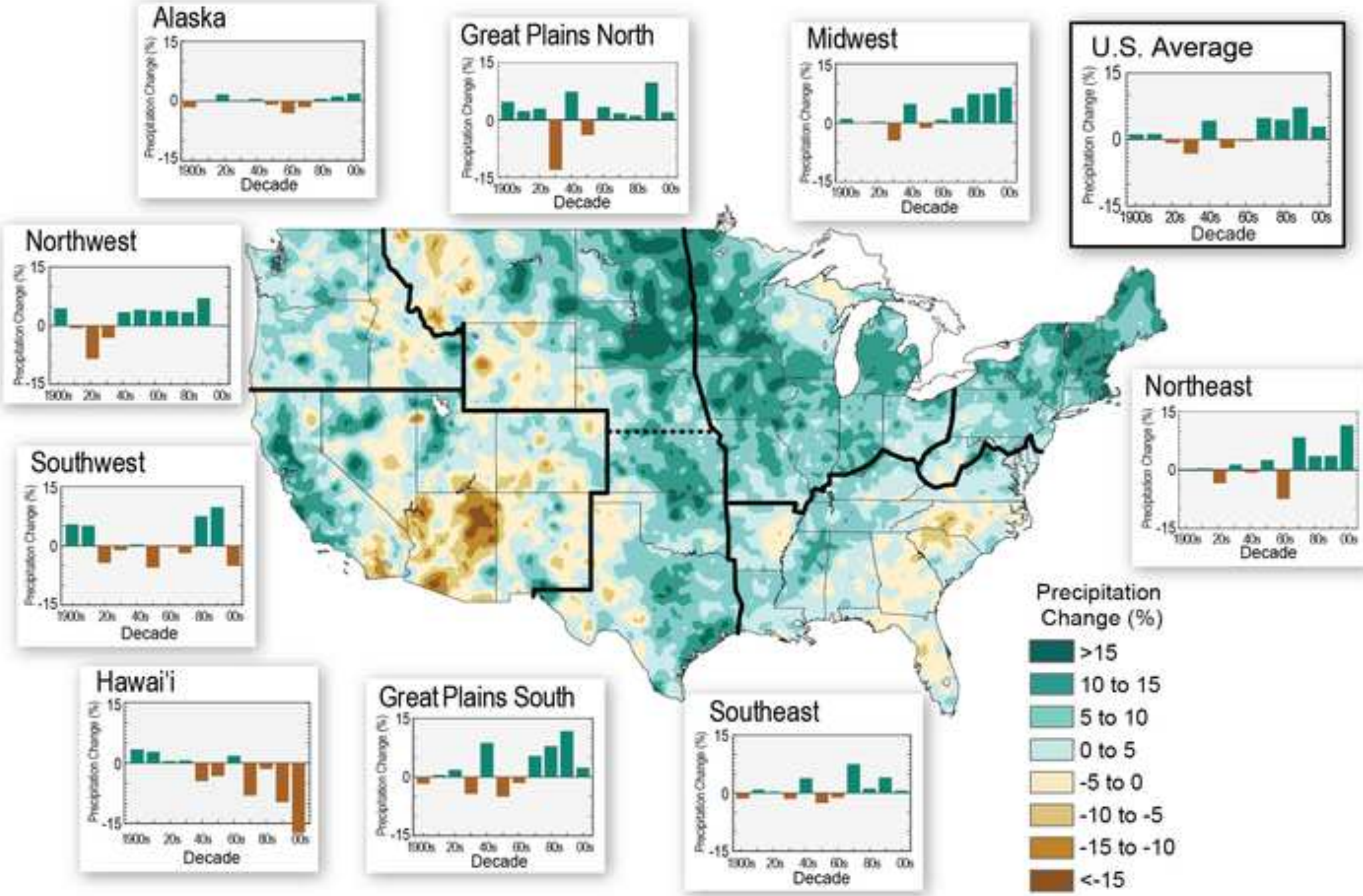

Alaska
Great Plains North
Midwest
U.S. Average
Northwest
Northeast
Southwest
Hawai'i
Great Plains South
Southeast
Precipitation Change (%)
Decade
1900s
20s
40s
60s
80s
00s
15
0
-15
Precipitation Change (%)
>15
10 to 15
5 to 10
0 to 5
-5 to 0
-10 to -5
-15 to -10
<-15

Figure 4

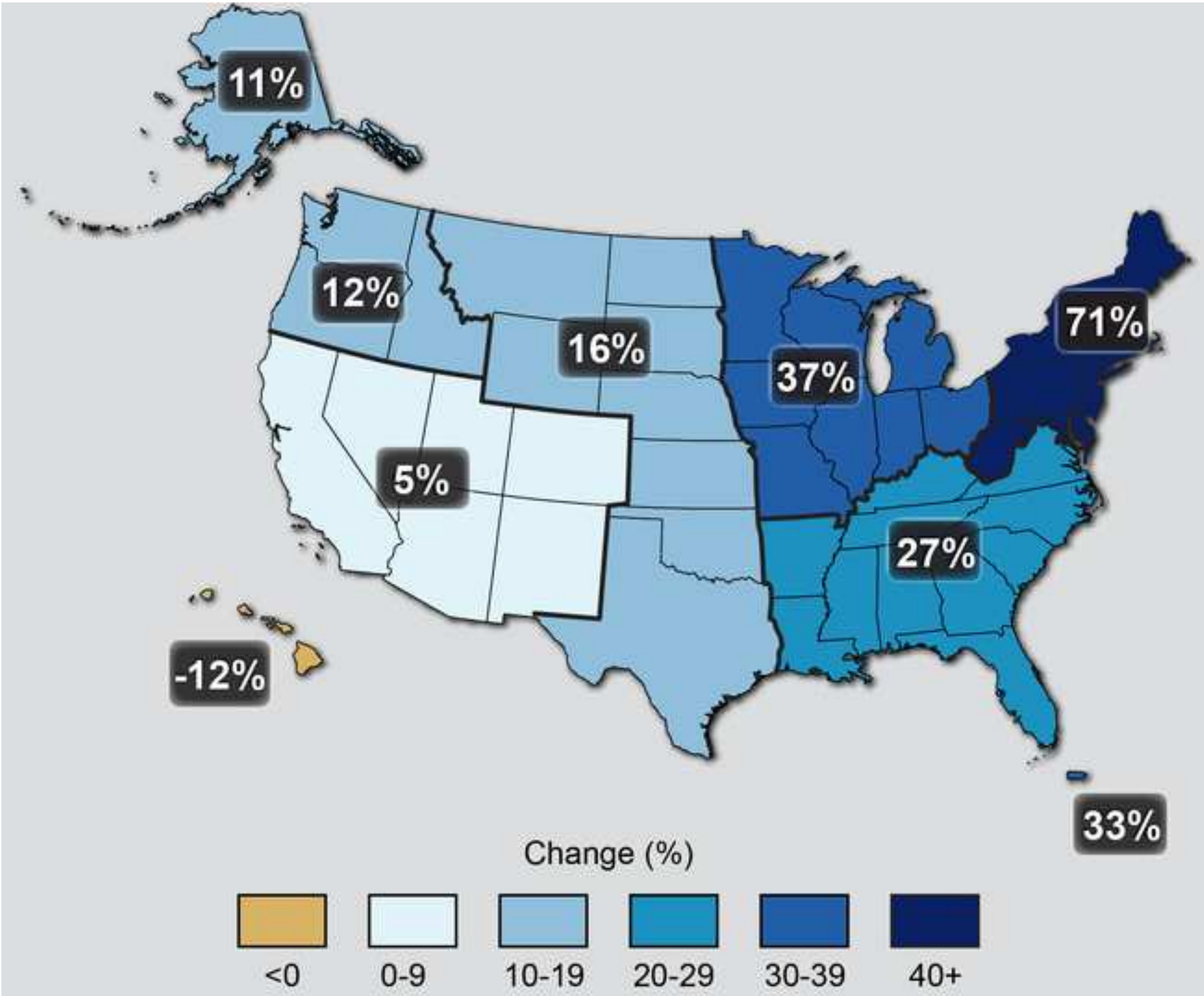
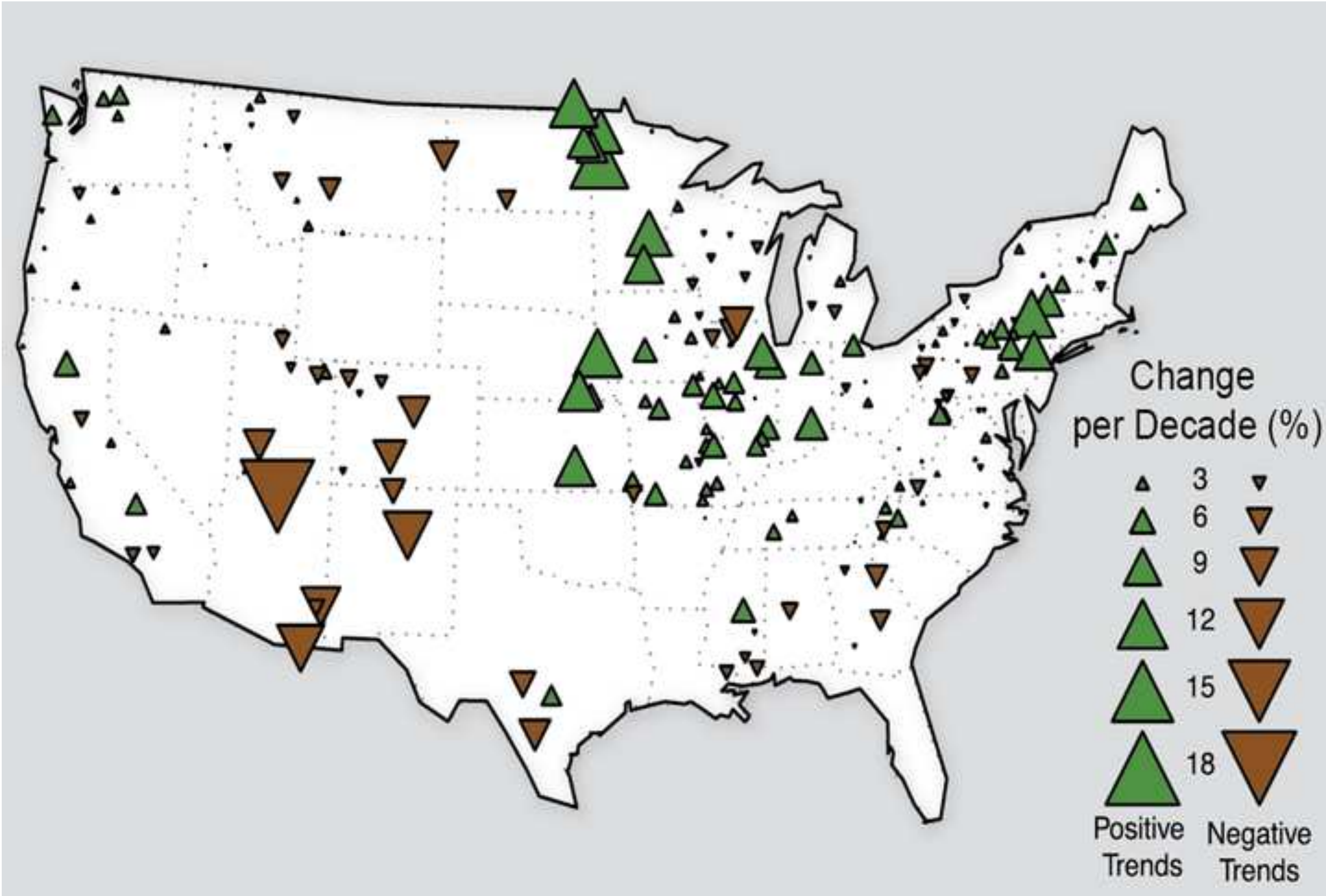


Figure 5


Change
per Decade (%)
3
6
9
12
15
18
Positive Trends
Negative Trends