2015 Project Abstract
For the Period Ending June 30, 2019

PROJECT TITLE: Understanding Water Scarcity, Threats, and Values to Improve Management
PROJECT MANAGER: Bonnie Keeler
AFFILIATION: University of Minnesota
MAILING ADDRESS: 301 19th Ave. S
CITY/STATE/ZIP: Minneapolis, MN, 55455
PHONE: (612) 625-8905
E-MAIL: keeler@umn.edu
WEBSITE: http://z.umn.edu/keeler
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2015, Chp. 76, Sec. 2, Subd. 04a

APPROPRIATION AMOUNT: $234,000
AMOUNT SPENT: $234,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results

We used advanced techniques to create the best available foundational climate change projections for Minnesota. Results show consistent or increased annual precipitation, but changing timing of rainfall, more intense rain events, and longer dry spells. We project winters with several fewer weeks of frost, and summers with significantly more days above 95°F.

Overall Project Outcome and Results

We created high-resolution climate change projections for Minnesota using the best available techniques. State agencies, local governments, private sector engineers, and other climate data users will be able to build freely off the foundational data we have created to make plans that are more prudent for the future of Minnesota. To ensure our results were not sensitive to any one model or year, we averaged the results of five models and further averaged the results over four 20-year scenario periods, 1989-1999 historical, 2040-2059 moderate emissions, and 2080-2099 moderate and high emissions. This gives us confidence that observed changes are the result of long-term changes and not the weather on a single year or model.

The overall trend for the state found in previous global modeling is for a warmer at wetter future. Our work adds local nuance not possible in global models. We find that the timing of precipitation will change, with more precipitation in the spring and early summer, more intense rain events, and longer dry spells between events. The north shore region of the state had the most pronounced increase in both quantity and intensity of precipitation by the end of the century. Infrastructure in the region will have to contend with twice as much precipitation in May, already among the wettest months, and up to 50% more precipitation in the largest 5-day rainfall total in an average year. Corn and soy yields declined by as much as 25% in the majority of scenarios and regions. We also project up to 30 additional days with highs 95°F or hotter.

We also assessed if climate change and increased water withdrawals could lead to water scarcity in the state. We did not find evidence for broad-scale scarcity, but we do highlight watersheds that may consider shifting some of their withdrawals to surface water. We also note that further research is required to capture short-term depletion local effects of withdrawals on surface features.

Research Products

Project Results Use and Dissemination

Product File Name or URL	Description
Practitioner Survey Synthesis.docx	A summary of the key findings from our survey of

	practitioners about what climate change data products would be the most useful to their work in Minnesota.
practitioner_survey.pdf	The survey we distributed to practitioners to understand their needs and uses of climate data.
https://z.umn.edu/climate-change-data	The future location of the climate data we produced. The standard practice in the climate modeling field is to publish results in a peer-reviewed journal before distributed the underlying data. For access to data before they are posted publicly, inquire with Tracy Twine (twine@umn.edu)
MPARS_data_quality_assurance.docx	Our approaches used to quality control the withdrawal data we used.
Climate_change_and_MN_water_final_report.pdf	High-level, accessible overview of the most notable climate change projections we identified in the state. A key tool for local planners to identify potential issues that require further investigation.
derived_climate_variables.xlsx	List of climate data products we derived and intend to distribute after publication.
water_consumption_coefficients_appendix.pdf	Appendix of water consumption coefficients
water_scarcity_methods_supplement.pdf	Detailed supplementary methods describing water depletion calculations.

Dissemination

Due to the universal applicability of climate to humans and the environment, we invested extra effort in preparation for disseminating this work. We surveyed practitioners to identify the types of climate data that are most needed to make decisions and manage resources in the state. We have publicized this work in numerous presentations, including the Clean Water Council, the Department of Health, the Department of Natural Resources and county level managers. We are also working to make much of the underlying data produced as a part of this research readily available to the public. Because the raw data is often challenging for non-specialists to work with, we invested considerable resources in interpreting the results in the accompanying final report.

For scientific audiences, in addition to the underlying data, we are planning three publications and at least one conference presentation based on this work. We already have plans to include these data in other research on irrigation trends and drinking water management in Minnesota.

Finally, as with most of our work, we will write a brief, accessible blog post to highlight and share this work with a broad audience.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2015 Work Plan

Date of Status Update Report: August 16, 2019

Final Report

Date of Work Plan Approval: 15 October 2014

Project Completion Date: June 30, 2019

PROJECT TITLE: Understanding Water Scarcity, Threats, and Values to Improve Management

Project Manager: Bonnie Keeler

Organization: University of Minnesota

Mailing Address: 301 19th Ave. S

City/State/Zip Code: Minneapolis, MN, 55455

Telephone Number: (612) 625-8905

Email Address: keeler@umn.edu

Web Address: http://z.umn.edu/keeler

Location: Statewide

Total ENRTF Project Budget:		
	ENRTF Appropriation:	**$234,000**
	Amount Spent:	**$234,000**
	Balance:	**$0**

Legal Citation: M.L. 2015, Chp. 76, Sec. 2, Subd. 04a

as extended M.L. 2018, Chapter 214, Article 4, Section 2, Subdivision 20

Appropriation Language:
$234,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to model and map statewide water scarcity and abundance; assess water-related risks to industry, municipalities, and ecosystems; and quantify the economic values of changes in water quality and quantity in order to inform long-term water sustainability strategies. This appropriation is available until June 30, 2018, by which time the project must be completed and final products delivered.

Carryforward; Extension (a) The availability of the appropriations for the following projects are extended to June 30, 2019: (4) Laws 2015, chapter 76, section 2, subdivision 4, paragraph (a), Understanding Water Scarcity, Threats, and Values to Improve Management

I. PROJECT TITLE: Understanding Water Scarcity, Threats, and Values to Improve Management

II. PROJECT STATEMENT:

Minnesota is rich in water resources, but growing and diversifying demands on water have led to water stress, declining lake levels, and threats to water quality. Compared to other states, Minnesota still retains a comparative advantage in water resources needed to support healthy communities and economic development. In order to secure a long-term sustainable water future, managers need to be able to predict changes in the availability and quality of water, especially in response to emerging threats to water including climate change, land-use change, and development. Information is also needed on the economic value of our clean water resource.

Previous work on water sustainability in Minnesota includes visioning assessments (e.g. the state water plan and the water sustainability framework), and index models and planning tools (e.g. Environmental Quality Board water availability project). While these projects provide snapshots of water sustainability, they do not account for feedbacks between climate and land-use, rely on outdated climate models and data, and cannot be used to evaluate alternative scenarios that capture future threats to water sustainability. We propose to address these gaps through an integrated biophysical and economic analysis of water sustainability in Minnesota. Our proposed work includes the following three activities: 1) parameterizing and applying a statewide water balance model using downscaled climate data, 2) assessing threats to water sustainability and evaluating the impacts of those threats on water quality and quantity, 3) quantifying the economic impacts of changes in the availability of clean water to support recreation, health, industry, and other water-related services.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of*:* January 2016

The project team began work on Activities 1 -3 as described in the project workplan. A postdoctoral researcher was hired to assist Dr. Twine and began work on climate modeling to be integrated into the Agro-IBIS water balance model. Dr. Brauman compiled and interpreted water use data with a student volunteer. The water data represent water use by different sectors in Minnesota. This work was presented at the American Geophysical Union Annual Meeting in San Francisco, CA in December of 2015. Dr. Keeler hired a Research Assistant on the project who has initiated work on water quality valuation including assembling data on different economic values of water for Minnesota.

Project Status as of: July 2016

Dr. Keeler and Research Assistants collected water costs and valuation data, including reviewing the literature and consulting experts on the health impacts of nitrate exposure and sensitivity analyses related to different kinds of water-related costs. Dr. Brauman worked with a Master's student to post-processes water withdrawal data from 1988-2014 from the Minnesota DNR Permitting and Reporting System (MPARS). Additional geographic data have been overlain with withdrawal data, withdrawal data have been aggregated into a variety of reporting units, and water use categories have been streamlined for analysis. Guidelines for converting water withdrawal to water consumption were also standardized, and an additional dataset of water consumption for Minnesota is nearly complete. Dr. Twine has compiled one historic and one future land use scenario for IBIS modeling. One (of five proposed) global climate model has been used to create one downscaled climate dataset for Minnesota for both historic and future climate scenarios. Post-doctoral fellow is being replaced (September 2016).

Project Status as of: January 2017

Work on the project was paused temporarily in late 2016 while Dr. Twine searched for a new researcher to continue the statewide climate simulations and Agro-IBIS modeling. Ultimately a researcher was hired and two additional model simulations under Activity #1 were completed, with others underway. Dr. Brauman completed standardization and post-processing of water withdrawal data. Work on economic analyses and water valuation will continue when water simulations are completed in the next few months.

Project Status as of: July 2017. After a delay caused by issues with data storage for climate and model simulations, work on the climate downscaling and Agro-IBIS runs continue. Two additional global climate models have been run with data downscaled to 10km over the Midwest region using the WRF model. Two research assistants supervised by Dr. Keeler worked on water valuation as part of Activity #3 and in the development of treats and scarcity data for future water risks as specified in Activity #2. Work on the project will ramp up in fall when final climate simulations are completed and coupled with simulations of water supply statewide.

Project Status as of: January 2018. Climate modeling continues albeit at a slower pace than anticipated at project outset. Six of eight global climate models have been dynamically downscaled to 10km resolution for the state of Minnesota. Despite delays related to data storage and model simulations, we don't anticipate any problems with getting all planned runs complete by June 2018. Historic and future outputs of one of the six global climate models have been successfully run through the Agro-IBIS model, producing climate, yield, and water-balance data statewide. We developed and tested a protocol for converting Agro-IBIS outputs into a file format compatible with water scarcity and ecosystem services modeling in Activities 2 and 3. We completed testing of overlay analyses using climate, IBIS, and ecosystem services metrics data to visualize results. Work has also progressed on outlining project manuscripts and data storage and dissemination protocols.

In summary, the outcomes described in Activity #1 have been delayed due to staffing and computing constraints. We have addressed these issues and climate simulations and water balance modeling is proceeding as originally planned. Activity #1 outcomes are expected to be completed by June 30th, 2018. Outcomes described in Activities #2 and #3 depend upon climate data produced in Activity #1. As a result, these outcomes have also been delayed. Project leads Bonnie Keeler and Kate Brauman have secured funding through a USDA AFRI grant in collaboration with Dr. Mae Davenport (Univ of Minnesota) to continue to conduct research on water scarcity and impacts on ecosystem services in Minnesota. The grant "Understanding and Building Capacity to Address Changing Water Availability in the Upper Corn Belt" (Proposal Number: 2016-10226, end date April 2020) will supplement the existing LCCMR award and provide additional funding to create research products that build upon the climate modeling in Activity #1. As such, we have updated the outcome completion dates below to reflect revised estimates for project deliverables. More details on each outcome are described below.

Amendment request: The project team requests legislative approval to extend the project end date to June 30th, 2019 and allow for carryover funds remaining in the project to be spent over the upcoming fiscal year. The Research Assistant assigned to this project accepted a different job and will be leaving the University effective March 19th. We do not have capacity within our current team to re-allocate this effort and will be unable to advertise and hire a new staff member to complete the remaining research activities by the original project end date of June 30th, 2018. An extension to June 30th, 2019 will allow our project time to hire a new research assistant and complete remaining deliverables.

Amendment Approved: May 30, 2018

Project Status as of: March 2019.

In this reporting period we completed several GCM runs for all scenarios and time periods. As a result we have enough model outputs to use an ensemble approach, thus making our projections more robust. Because the infrastructure for running the GCMs is complete, adding additional models is a function of computer processing time rather than staff time.

With the influx of model outputs we needed to develop extensive post-processing capacity to reduce the thousands of maps generated in activity one to manageable datasets suitable for further analysis. This included basic post-processing techniques such as converting the data and calculating averages over different spatial units and time horizons, and also more advanced techniques to deal with the special challenges of water.

To identify changes in water availability, we account for both changes in input from precipitation, but also changes in input from upstream watersheds and track how much each watershed contributes to the watersheds below it.

We also have analyzed DNR well permit data to calculate the amount of groundwater being consumed and the amount converted to surface water. This will be instrumental for both identify scarcity concerns as well as estimating the impact of climate and water variability on humans and ecosystem services.

Finally, we have engaged in a broad outreach effort to raise awareness about our forthcoming data products and to solicit crucial feedback from end users on the data formats and projections that would be most useful for their work. We accomplished this by surveying practitioners from the non-profit, private, and many agencies in the public sectors. The survey results will inform the data products we produce and also provide a list of users ready to start using them.

Overall Project Outcomes and Results:

We created high-resolution climate change projections for Minnesota using the best available techniques. State agencies, local governments, private sector engineers, and other climate data users will be able to build freely off the foundational data we have created to make plans that are more prudent for the future of Minnesota. To ensure our results were not sensitive to any one model or year, we averaged the results of five models and further averaged the results over four 20-year scenario periods, 1989-1999 historical, 2040-2059 moderate emissions, and 2080-2099 moderate and high emissions. This gives us confidence that observed changes are the result of long-term changes and not the weather on a single year or model.

The overall trend for the state found in previous global modeling is for a warmer at wetter future. Our work adds local nuance not possible in global models. We find that the timing of precipitation will change, with more precipitation in the spring and early summer, more intense rain events, and longer dry spells between events. The north shore region of the state had the most pronounced increase in both quantity and intensity of precipitation by the end of the century. Infrastructure in the region will have to contend with twice as much precipitation in May, already among the wettest months, and up to 50% more precipitation in the largest 5-day rainfall total in an average year. Corn and soy yields declined by as much as 25% in the majority of scenarios and regions. We also project up to 30 additional days with highs 95°F or hotter.

We also assessed if climate change and increased water withdrawals could lead to water scarcity in the state. We did not find evidence for broad-scale scarcity, but we do highlight watersheds that may consider shifting some of their withdrawals to surface water. We also note that further research is required to capture short-term depletion local effects of withdrawals on surface features.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Statewide water balance and land surface modeling (Agro-IBIS modeling)
Description: Human activities have altered landscapes in ways that affect the fluxes of energy, water, and carbon between the atmosphere and the land surface. Understanding the relationships among these factors and how they are likely to change as a result of changes in land cover, land management, and climate is critical for responsive and sustainable management of water and land resources. For example, removing vegetation or converting from one land-use type to another (e.g. conversion of grassland or forest to agriculture) has been shown to significantly increase runoff and streamflow. Changes in land use can also affect the delivery of nutrients and sediment to surface waters and groundwater. The processes that dominate water fluxes between the land surface and atmosphere and fluxes of nutrients and sediments are complex and vary over time and space. Addressing questions about how changes in land use, water use, and climate will affect the amount and quality of water seasonally and spatially requires sophisticated modeling approaches.

We propose to use an adaptation of a dynamic global vegetation model (DGVM) that includes modules for vegetation canopy physics, soil physics and hydrology, phenology, and ecosystem biogeochemistry. The model, called Agro-IBIS, was developed specifically for the continental US and can represent common cropping systems represented in Minnesota such as corn, soybean, and wheat, along with natural ecosystems of grasslands, forests, and shrublands (Figure 1). Agro-IBIS allows for variable fertilizer inputs as well as irrigation and farmer management decisions.

Another key advantage of using a DGVM is the ability to use the model to understand the consequences for water quality and quantity due to specific interventions in different parts of the state. Climate, as well as the coverage of natural and managed ecosystem types (e.g. forests, crops, grasslands) varies across Minnesota. Whereas many other models do not directly simulate the growth of vegetation in their water balance calculations, the Agro-IBIS model will allow us to make predictions about changes in water fluxes (to evapotranspiration, surface runoff and groundwater recharge) and nutrient losses based on local climate, vegetation, and management in each pixel. The ability to directly simulate the biological and physical response of vegetation to changes in climate in individual grid cells will produce greatly improved water quantity and quality estimates over previous statewide models (e.g. 2008 LCCMR-Project 4a).

Our work will also take advantage of the latest advancements in future climate projections and incorporate these data into our water balance modeling. Agro-IBIS uses as input high-resolution climate data down-scaled from the most recent CMIP5 global climate model output (used in the 2013 IPCC AR5 report). These updated climate models have improved estimates for how water availability will change in the future, including variability in the seasonality and intensity of precipitation out to the year 2100. We will downscale global resolution climate data (currently at 1-3 degree resolution – about 100-300 km) to a 10 km resolution for input into the Agro-IBIS model. This downscaled climate data product will be useful for our water balance modeling in Minnesota, as well as for other analyses and models that rely on downscaled climate information.

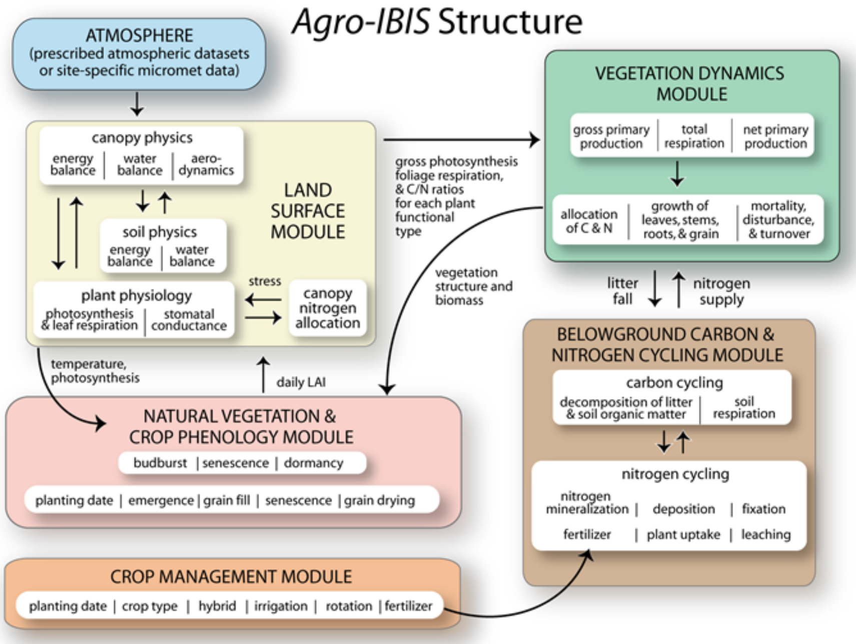


Figure 1: Schematic of the Agro-IBIS model. Agro-IBIS simulates multiple ecosystem processes within the natural biomes of forests, grasses, and shrubs, as well as crops including maize, soybean, and wheat.

We will use Agro-IBIS to simulate the growth and water use of vegetation at every grid cell statewide. Outputs of the model include water loss through evapotranspiration, drainage, and runoff for any time period of interest. We will also use the model to simulate changes in nutrient fluxes as a function of changing agricultural or land-use practices. The model can also account for irrigation and municipal, domestic, and industrial water use and adjust water balance calculations accordingly.

In order to run the model in Minnesota, we will need to process soils, land use, and climate data to parameterize the model. As noted above, this activity requires downscaling global climate data from the most recent global climate models for use at finer spatial resolutions in Minnesota. Where available, we will also assemble current information on the location and consumptive rates of water users (irrigation, municipal consumption, and other water-intensive industries). Outputs of the model will include gridded maps of water balance, including quantification of streamflow and groundwater recharge and changes in water quality by sub-watershed.

Summary Budget Information for Activity 1:

ENRTF Budget: $ 73,153
Amount Spent: $ 73,153
Balance: $ 0

Outcome	**Completion Date**
1. Processed soils, land-use, and downscaled climate data needed for water balance calculations and model calibration. Where available, we will also assemble current information on the location and consumptive rates of water users (irrigation, municipal consumption, and other water-intensive industries).	*Fall 2015*
2. Gridded map of water balance, including quantification of streamflow and groundwater recharge by sub-watershed.	*Summer 2018*
3. Statewide water scarcity metric that will identify regions of annual or seasonal water stress that can be used for planning and assessment.	*Summer 2018*

Activity Status as of*:* January 2016: Dr. Twine and a post-doctoral associate supported by this project have been processing data from six different global climate models to generate input data needed to parameterize the Agro-IBIS model. The models represent different global greenhouse gas emissions scenarios for future dates 2050 and 2100. Models are also run for historic time periods to calibrate and validate results. The model output from this activity includes five variables that will be used in the IBIS modeling; precipitation, temperature, relative humidity, incoming solar radiation, and wind speed. These parameters will be incorporated into IBIS along with other variables (soil texture, land use, land management, irrigation, etc) to yield spatially explicit data on evapotranspiration, soil moisture, surface runoff and drainage. The IBIS model will output data on water yield, runoff, and drainage to be incorporated into the water risk assessments of Activity 2 and the water valuation work in Activity 3.

Activity Status as of: July 2016
One complete climate downscaling simulation has been performed (of the five proposed global climate models). This includes creating five variables that will be used in the IBIS model, for both historic and future climate scenarios. The post-doctoral fellow has left the project for permanent employment at WindLogics, Inc. As of July, replacement personnel has been identified and paperwork is being assembled to hire her. The former post-doc will meet with us to ensure a smooth transition. Considering the speed with which the first model was run, we can likely create more than the proposed five global climate model simulations (perhaps up to 10) for no additional cost or project time. In August, Twine will begin IBIS model simulations and by September we should have the modeling personnel hired.

Activity Status as of: January 2017
New personnel has been working on the project since September 2016. Two additional model simulations have been run. We have been carrying out model simulations using the WRF model (10-km resolution) at the Minnesota Supercomputing Institute (MSI). We dynamically downscaled the following models: CNRM-CM5 (France), MIROC5 (Japan), BCC-CSM1-1 (China). Each of these models were previously vetted as to their performance over the Upper Midwest, and Minnesota, in particular. We pre-processed the climate model data

to bias-correct the GCM data for the historical period before ingesting in the regional model, and we again post-processed the data after the simulations were complete to verify that the historical period was simulated accurately. We then processed data into a format suitable for ingestion into the Agro-IBIS model and have been testing Agro-IBIS over our study domain with the climate data input. We have secured computing time on MSI resources for 2017, and have begun numerical modeling of the next batch of simulations using all resources available to us from MSI.

Activity Status as of: July 2017
Climate modeling simulations have been delayed because of limitations of the Minnesota Supercomputing Institute. A new fee policy (previously use was free for faculty with sponsored accounts) delayed work while we worked with MSI to create a work flow that would meet our needs. We were able to use climate simulations completed and paid for on a different project (that overlap with same resolution and scale) to advance work on this project while we address storage issues. Work is progressing but has been slowed while personnel moves files between storage disks after post-processing (a slow process). In the meantime, Twine has been quality checking all the down-scaled data and testing it in Agro-IBIS. GCM data are being post-processed into a more space-efficient format to speed up the workflow and facilitate faster iteration on future runs. So far we have completed two Global Climate Models - the CNRM model runs and the Chinese model. Another mode, MIROC, is up next. Our goal is to use eight GCMs, RCP 4.5 and 8.5 degree emissions scenarios, and several periods: 1991-2010, 2021-2060, 2080-2099. We do not anticipate any changes to project deliverables or outcomes, but storage and supercomputing issues have delayed progress on Agro-IBIS runs for a few more months.

Activity Status as of: January 2018.
Runs of the Global Climate Models (GCMs) continue as described in previous report. After reformatting datasets to speed workflow, we have now downscaled six GCMs for three time periods, with two more GCMs planned as space and computing permit. The GCM's produce daily time step data on temperature (min max), precipitation, relative humidity, wind speed, incoming solar radiation. The first downscaled suite (historic and future) of climate data have been run through Agro-IBIS. Agro-IBIS produces the following outputs – evapotranspiration, incoming radiation, leaf area index, net primary productivity, runoff (surface and sub-surface drainage), soil temperature, soil moisture, soil carbon, above and below-ground biomass, crop yield, and growing degree days, among other outputs. Historic results were validated with state-level reports of observed crop yields. We are formatting Agro-IBIS model results to be used in Activity 2 tasks and formatting climate model results for public presentation (see Figure below for example output). We are working on best practices to archive this data and present the data to the public.

In summary, outcome #1 is complete (processed data on land use, soils, etc) and has formed the basis of inputs to the climate and water balance modeling. A gridded map of statewide water balance (Outcomes #2) is in the works with one scenario complete and the remaining scenarios expected to be completed by June 2018. Similarly, Dr. Brauman's development of a state-wide water scarcity metric is also expected to be complete by June 2018, assuming climate modeling continues at its current pace.

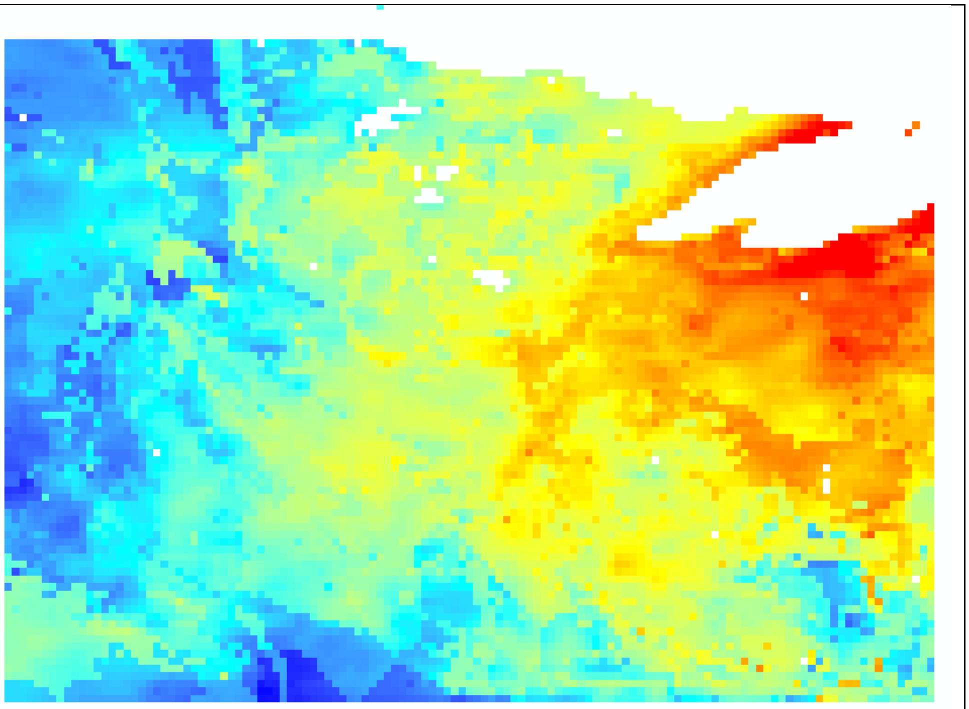


Figure: Data from the most recent Agro-IBIS model runs demonstrating the domain and resolution of model outputs.

Activity Status as of: March 2019
Downscaled climate data from three GCMs has been processed through the Agro-IBIS model. Averaging across these three models will provide a more robust projection of future climate trends, and the analytic computer software is being developed to allow for these cross-model averages. Surface and groundwater withdrawals have been analyzed from DNR permitting data and water consumption rates derived from that information using most current academic research. Surface water availability by month has been calculated for future climate scenarios, incorporating flow from upstream to downstream hydrologic units. Methods to apportion soil drainage into groundwater recharge and stream base flow are currently being investigated with the goal of maintaining comparability to methods employed by state agencies. Flexible, transparent, and automated computer program has been developed to calculate water depletion by 8-digit hydrological unit by month, allowing for comparisons between different climate and consumption scenarios.

Final Report Summary:
This project received much more attention than we anticipated. While our objectives to evaluate water resources across the state continue to be prioritized, scientists, policymakers, and the general public were extremely interested in our projections of temperature and precipitation—variables we considered input to address our project objectives. This interest allowed us to share personnel resources to bring on a graduate student advised by project scientist Liess who ran one of the global climate models in our suite to examine how four global climate anomalies (e.g., El Niño-Southern Oscillation) interact to affect climate in Minnesota and the rest of North America. PI Twine and Liess also mentored a high school student who evaluated variables in addition to those proposed to look at how diurnal temperature range (that is, the difference between the daily maximum and minimum temperatures) is projected to change, and how the models expect snow depth to vary in the future.

We now have complete datasets of climate projections downscaled from 7 global climate models, two global emissions scenarios (RCP4.5 and RCP8.5), and two future time periods (2040-2059, 2080-2099). Variables include daily maximum and minimum temperature, daily precipitation, daily relative humidity, daily wind speed, and daily incoming solar radiation. These datasets have driven the Agro-IBIS model to simulate monthly variables of surface runoff, drainage, evapotranspiration, and yearly values of yield for corn and soybean as well as productivity of trees and grasses. All variables have been mapped at 10km grid cell resolution across the state and highlight regions of potential future water and heat stress that result in lower productivity (see final report supplement). Future work will run similar model experiments to test adaptations like irrigation, changing planting date and cultivar, etc.

We plan to submit four scientific manuscripts to peer-reviewed journals from this activity. We have and plan to present this work at scientific conferences and other venues. Please see the Dissemination section for details on how this work will be made available. The impact from this work is expected to be far-reaching with interest from scientists who want these data as drivers to their ecological models, cities tasked with developing climate adaptation plans, and designers who are searching for evidence for building resilient infrastructure (both urban and rural). We are working with the MN Dept. of Natural Resources State Climatology Office to insert these data into their climate viewer for public viewing (climate.umn.edu). Finally, this activity serves as a pilot for future studies either here in Minnesota or other states who can devote resources to creating these projections. Climate models are constantly improved as we gain more observations and as computing power increases. We expect that our methodologies can be used in future studies to refine our projections of the future of Minnesota's water resources.

ACTIVITY 2: Water scarcity and threats assessment
Description: The outputs of the water balance model can be interpreted to identify regions of water scarcity or water stress. Quantifying and mapping water scarcity is crucial to managing shortages and finding solutions, such as identifying regions where it is important to re-use water or to anticipate tradeoffs among competing water uses. Periodic and localized scarcity of water is common, even in water-rich regions like Minnesota. Short term water scarcity can pose high economic and environmental costs, including lost economic development and investments in expensive infrastructure to transport or treat water. It is also important to consider both consumptive use of water as well as withdrawals, thus accounting for water that returns to a water source after use and becomes available for re-use. Evaluating water scarcity at high spatial and temporal resolution, and considering whether water demand is consumptive or re-usable, provides a more realistic estimate of water stress at any given location.

We will incorporate the results of the water balance modeling into an assessment of water scarcity which considers how metrics of scarcity change in the face of future threats. Water sustainability in Minnesota may change in the future as a function of changes in temperature and precipitation patterns, changes in the extent and intensity of water intensive industries, and changes in land use and land management such as new cropping systems or irrigation technologies. Agro-IBIS has the ability to assess the impacts of these threats on water balance calculations and water quality changes in individual grid cells and then these changes can be interpreted and mapped using different metrics of water scarcity.

We will also use the model to assess scenarios specific to different rates of water withdrawal and consumption. For example, we will estimate total water withdrawals for the five most important water use sectors: irrigation, livestock based agriculture, manufacturing, electricity production, and households and small businesses. Where data are not available at the local scale, we can estimate water use in the manufacturing and domestic based on data from county and state-level statistics and reports and allocated to sub-county grid cells based on geo-referenced population density and urban population maps. For example, water withdrawals for livestock can be computed by multiplying the number of animals per grid cell by the livestock-specific water use intensity. We can use these data to project impacts of likely future development.

We will then use the outputs of the Agro-IBIS model to map regions of water scarcity or depletion. Water depletion is defined as the ratio of consumptive water use by human activities to the amount of renewable freshwater available in a watershed on annual, seasonal, and inter-annual time scales. We will evaluate "seasonal depletion" to describe watersheds that exceed 75% depletion in any month of an average year and "drought depletion" to describe watersheds in which monthly depletion exceeds 75% within the historic range of water availability. In addition, we will evaluate the sensitivity of water scarcity to defining stress conditions at different levels of depletion. Water depletion as characterized here differs from other indicators of water scarcity in three important ways: temporal evaluation, spatial resolution, and consideration of consumptive water use rather than water withdrawals.

These maps of water scarcity or depletion, evaluated seasonally and spatially, will greatly improve previous estimates of water sustainability in Minnesota. Because the metrics are based on underlying biophysical and climate drivers represented in the Agro-IBIS model, we can simulate a wide variety of alternative futures and conditions that may affect water security. In addition to changes in water availability, we will also use the model outputs to identify regions where there are likely to be changes in water quality. The model structure and analytical framework allow for investigations into the tradeoffs between water quality and quantity statewide. Different regions may experience different future stressors for water sustainability, with some regions facing growing concerns about water quality, whereas other regions may experience water shortages. We will map these challenges to water sustainability statewide, including identifying regions facing dual stressors to both water quality and quantity.

Summary Budget Information for Activity 2:		
	ENRTF Budget:	**$ 97,869**
	Amount Spent:	**$ 97,869**
	Balance:	**$ 0**

Outcome	**Completion Date**
1. Maps capturing the location and impacts of threats to future water quality and quantity. Where there is uncertainty about water use or future threats, we will use scenarios to explore many plausible alternatives.	*Fall 2018*
2. Identification of key tradeoffs, risks, and vulnerabilities of water-dependent sectors and groundwater-dependent ecosystems (i.e. lakes, trout streams) based on modeled scenarios of future climate, land and water-use.	*Winter 2018*

Activity Status as of*:* January 2016
Dr. Brauman, with the assistance of a volunteer intern, collected historical data on water use by different sectors in Minnesota from state agency sources and compiled these data in a database that will be used by the project. The analysis of water use by sector was presented at the Annual Meeting of the American Geophysical Union in San Francisco, CA in December of 2015. Dr. Brauman and Dr. Twine began planning integration of IBIS modeling in Activity 1 with different scenarios of water use to complete the water scarcity metrics planned for Activity 2.

Activity Status as of: July 2016
Dr. Brauman worked with a Masters student to post-processes water withdrawal data from 1988-2014 from the Minnesota DNR Permitting and Reporting System (MPARS). Additional geographic data have been overlain with withdrawal data, withdrawal data have been aggregated into a variety of reporting units, and water use categories have been streamlined for analysis. Guidelines for converting water withdrawal to water consumption were also standardized, and an additional dataset of water consumption for Minnesota is nearly complete.

Activity Status as of: January 2017
Dr. Brauman completed post-processing of water withdrawal data to be used for the water scarcity analysis.

Activity Status as of: July 2017.
Dr. Brauman has suspended her involvement in the project until the Agro-IBIS runs are completed this fall. In the meantime, Dr. Keeler has been working with two research assistants to obtain and process spatial data that will

be needed for the scarcity and threats mapping. This includes a new spatial layer and associated modeling of land use change that can be coupled with the Agro-IBIS climate simulations. We also downloaded and processed spatial data on the extent of tile drainage by county – another factor in water-related impacts of changing land use and climate.

Activity Status as of: January 2018
Dr. Keeler's team has developed a land use change model for Minnesota that can be used to estimate the spatial location of future threats to water resources. The land change layer is currently being tested, along with protocols for data conversion of Agro-IBIS outputs, to ensure all spatial model outputs are compatible. As Agro-IBIS runs are completed over the next few weeks, Dr. Brauman will begin converting IBIS outputs into spatial maps of water scarcity for Minnesota.

Outcome #1 (maps of current and future threats to water) will integrate the land use data developed by Keeler's team and the water scarcity maps developed by Dr. Brauman (building on the climate modeling). Once the climate data are finalized, we estimate an additional three months to create and refine these visualization products. Outcome #2 (identification of key tradeoffs) will be described in our final LCCMR report and a future peer-reviewed publication, anticipated for early 2019.

Activity Status as of: March 2019
We have automated much of the post processing of climate model outputs. The outputs take the form of a separate map for each month, year, variable, scenario, and model combination, resulting in thousands of maps to analyze. Our automation allows us to aggregate large amounts of data both over time and space so that we can identify and communicate important trends in the data.

We also linked model outputs to hydrological flow data to account for upstream contributions when measuring scarcity. This method recognizes that available surface water in a given sub-basin includes considerable flows from these upstream counties. Deducting water that is consumptively used in a watershed, we account for export flows from surface runoff, natural groundwater to surface water base flow, and pumped groundwater, much of which ends up discharged into surface water. This allows us to develop a depletion measure that is sensitive to a given region's position in our complex river network.

A masters student from Dr. Keeler's lab worked with Dr. Brauman and Sean Hunt from the Department of Natural Resources to receive an updated (1988 - 2017) set of monthly withdrawal estimates reported through MPARS. Sean Hunt and the student collaborated to finalize the integrity of the data and to standardize it moving forward. Additionally, a withdrawal to consumption coefficient map was created for the 55 use type categories in the MPARS data based upon a literature review by Dr. Brauman. The consumption coefficient map was applied to the validated withdrawal data to have an updated consumption estimate within the state during the 30 year period.

Final Report Summary:
For Activity 2, we compiled data on water withdrawals from 1988-2017 from the Minnesota DNR Permitting and Reporting System (MPARS). The project team worked closely with MN DNR employee Sean Hunt to identify and address data errors including missing data at either monthly or annual time steps, mis-matches between reported monthly and annual data, and reporting discrepancies between years. Data integrity approaches were automated by our project team and shared with the DNR.

Post-processing of water withdrawal data included developing and applying Minnesota-relevant conversion factors to partition water withdrawal data between water consumption and return flow for the 55 categories of water use in the MPARS data set, streamlining water use categories for analysis and future projections, calculating surface and groundwater withdrawal, consumption, and return flow, and aggregating these data at the watershed scale.

Future water use in Minnesota was combined and predicted for 5 categories of water use (water supply, industrial, heating/ cooling, irrigation, and other based on the relationships between historic water use, climate, and population variables. Historic water use data were regressed against precipitation and population and the resulting relationships were used in conjunction with our climate projections and projections from the MN State Demographic Center to predict future water demand for a range of scenarios.

We developed a simple water watershed-scale water balance model to integrate water availability data from Activity 1 with water use data developed in Activity 2. Water availability data for a range of future climate scenarios from Activity 1 was aggregated at the watershed scale in an automated procedure following extensive data quality review. These outputs were then routed downstream using a hydrologic routing scheme to account for upstream contributions when measuring scarcity. Water that is consumptively used in a watershed is not available downstream, but return flows from surface runoff and transfers from groundwater to surface water due to return flows are accounted for. Natural groundwater to surface water base flow is also represented, following USGS practice. Water scarcity was assessed for both ground and surface water based on the ratio of water consumption to renewable water availability.

Outputs from the activities above include guidelines for data quality assurance for reported water withdrawal data. These are critical, as in MPARS Minnesota maintains perhaps the most comprehensive water use data set in the US and the consistency and reliability of these data will improve both management and research. We have developed maps of historic water withdrawal, data and maps of historic water consumption, and maps of projected future water withdrawal and consumption that provide easy-to-use base data for both managers and researchers asking additional questions about Minnesota's water resources.

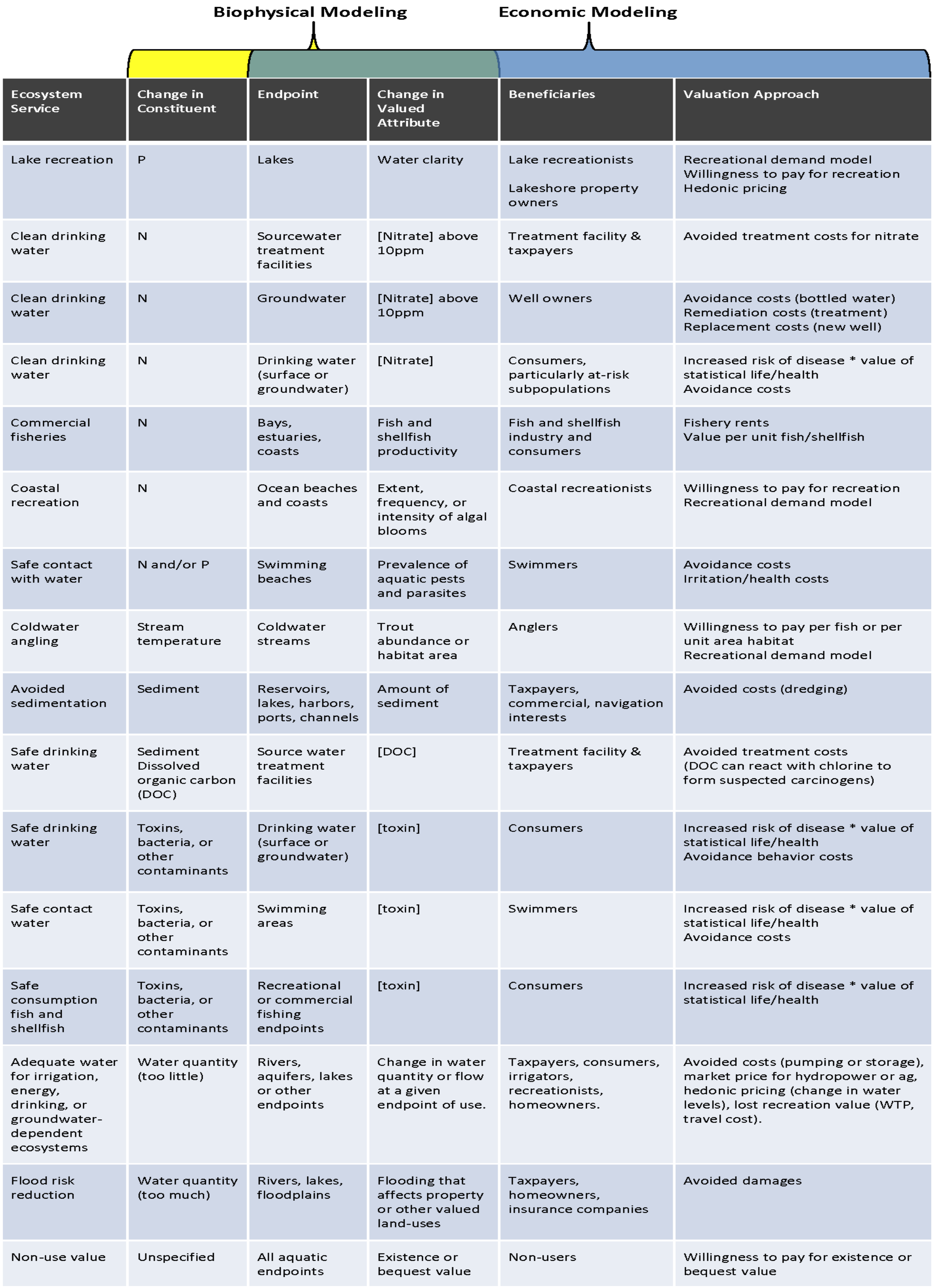
When analyzing the future precipitation data we found the annual quantity to be either similar to or greater than the historical reference period, and the most notable changes were in timing and intensity of precipitation. However, analyzing changes in groundwater availability in response to these short-term (e.g. 1-2 month) shifts in precipitation requires understanding the connectivity and porosity of geology statewide, which influences the speed with which precipitation becomes base flow. Base flow is groundwater contributing to rivers and streams, thus becoming surface water and leaving the watershed. Accurately estimating how long groundwater remains locally is essential for assessing when a region's withdrawal rate will influence availability of groundwater for people and ecosystems. We consulted with specialists in hydrogeology at the Minnesota Geologic Survey and the United States Geologic survey to define the best set of assumptions to use in the absence of comprehensive statewide geologic data and prohibitively intensive modeling. We concluded that using a more conservative assumption that precipitation that goes to groundwater will become base flow within a year was most appropriate for this analysis. Depending on the connectivity of the underlying geology, this process can take weeks or years. If the process occurs quickly, groundwater quantity will be more sensitive to withdrawals during the longer dry spells we project for the state. By selecting a longer period, we can be more confident in any water depletion signs we observe, however, we also lose the ability to detect short-term depletion that could occur if irrigation demand increases in response to dry periods later in the growing season. We found one watershed that had consumption equivalent to 28% of its available groundwater in the mid-century period. This was the highest of any of the watersheds or scenarios analyzed, but is not extreme. Communities with greater than 25% annual depletion may have greater depletion on a short-term base and should consider surface water sources when expanding withdrawals. *In summary, broad scale water depletion is unlikely, but we encourage the use of our data products in local models that can capture changes over shorter time periods and can incorporate the effects of the local geology.*

ACTIVITY 3: Economic valuation of water-related ecosystem services
Description: We systematically underestimate the value of water in decisions and planning because we lack an accounting of the full costs associated with changes in water quality and quantity. In order to evaluate how modeled changes in water quality and quantity affect the health, livelihoods, and economic development in Minnesota, new spatial datasets and models are needed that quantify and value the impacts of changing water

quality and quantity on human wellbeing. We propose a comprehensive inventory of the value of water that can be used in cost-benefit studies, risk analyses, and return-on-investment calculations. The economic value of clean water includes costs associated with water treatment, lost property values, degraded recreational opportunities, beach closures and water-borne diseases, impacts to groundwater-dependent ecosystems, and water-related infrastructure investments. Many of these data are collected by state agencies, but have not been assembled and evaluated such that they can be used in spatial planning or integrated with alternative scenarios of water use (such as those generated by the model in Activities 1 & 2).

There are numerous approaches employed by economists to place an economic value on water-related ecosystem services. In brief, economists can ask respondents directly how much they would be willing to pay for a given improvement in water quality or quantity (stated preference methods). Alternately, economists can indirectly estimate the value of changes in the availability of clean water through observations of human behavior such as willingness to drive longer distances to visit areas of higher water quality (revealed preference methods). Additional approaches include estimating the costs associated with degraded water quality (e.g., sediment dredging, drinking water treatment), investing in water-related infrastructure (e.g. pipelines), costs associated with irrigation or other consumptive uses of water, or the costs associated with increased health risks due to contact or consumption of unsafe water.

There are five key benefits of clean water that are both policy-relevant and in need of more study in Minnesota: 1) the value of avoided health impacts associated with drinking water or contact with water through recreation, 2) the infrastructure and treatment costs required to maintain a clean and adequate supply of water for communities and industry, 3) the benefits associated with aquifer storage and groundwater-dependent ecosystems, 4) the economic values of lake and stream recreation, and 5) the value of clean water to support agricultural and livestock production. We will build on the water valuation framework introduced by Keeler et al. (2012, Figure 2) to collect cost data on these five sources of water values in Minnesota and integrate the results into models that related a change in water quality or quantity in a given region of the state to a change in a specific water-related value. The results will identify spatially where investments in improvements in water quality or quantity are likely to generate the greatest returns to public goods. Our analysis will also be the first comprehensive assessment of the value of clean water in Minnesota considering multiple sources of value (e.g. health, recreation, treatment and infrastructure costs).



Ecosystem Service	Change in Constituent	Endpoint	Change in Valued Attribute	Beneficiaries	Valuation Approach
Lake recreation	P	Lakes	Water clarity	Lake recreationists Lakeshore property owners	Recreational demand model Willingness to pay for recreation Hedonic pricing
Clean drinking water	N	Sourcewater treatment facilities	[Nitrate] above 10ppm	Treatment facility & taxpayers	Avoided treatment costs for nitrate
Clean drinking water	N	Groundwater	[Nitrate] above 10ppm	Well owners	Avoidance costs (bottled water) Remediation costs (treatment) Replacement costs (new well)
Clean drinking water	N	Drinking water (surface or groundwater)	[Nitrate]	Consumers, particularly at-risk subpopulations	Increased risk of disease * value of statistical life/health Avoidance costs
Commercial fisheries	N	Bays, estuaries, coasts	Fish and shellfish productivity	Fish and shellfish industry and consumers	Fishery rents Value per unit fish/shellfish
Coastal recreation	N	Ocean beaches and coasts	Extent, frequency, or intensity of algal blooms	Coastal recreationists	Willingness to pay for recreation Recreational demand model
Safe contact with water	N and/or P	Swimming beaches	Prevalence of aquatic pests and parasites	Swimmers	Avoidance costs Irritation/health costs
Coldwater angling	Stream temperature	Coldwater streams	Trout abundance or habitat area	Anglers	Willingness to pay per fish or per unit area habitat Recreational demand model
Avoided sedimentation	Sediment	Reservoirs, lakes, harbors, ports, channels	Amount of sediment	Taxpayers, commercial, navigation interests	Avoided costs (dredging)
Safe drinking water	Sediment Dissolved organic carbon (DOC)	Source water treatment facilities	[DOC]	Treatment facility & taxpayers	Avoided treatment costs (DOC can react with chlorine to form suspected carcinogens)
Safe drinking water	Toxins, bacteria, or other contaminants	Drinking water (surface or groundwater)	[toxin]	Consumers	Increased risk of disease * value of statistical life/health Avoidance behavior costs
Safe contact water	Toxins, bacteria, or other contaminants	Swimming areas	[toxin]	Swimmers	Increased risk of disease * value of statistical life/health Avoidance costs
Safe consumption fish and shellfish	Toxins, bacteria, or other contaminants	Recreational or commercial fishing endpoints	[toxin]	Consumers	Increased risk of disease * value of statistical life/health
Adequate water for irrigation, energy, drinking, or groundwater-dependent ecosystems	Water quantity (too little)	Rivers, aquifers, lakes or other endpoints	Change in water quantity or flow at a given endpoint of use.	Taxpayers, consumers, irrigators, recreationists, homeowners.	Avoided costs (pumping or storage), market price for hydropower or ag, hedonic pricing (change in water levels), lost recreation value (WTP, travel cost).
Flood risk reduction	Water quantity (too much)	Rivers, lakes, floodplains	Flooding that affects property or other valued land-uses	Taxpayers, homeowners, insurance companies	Avoided damages
Non-use value	Unspecified	All aquatic endpoints	Existence or bequest value	Non-users	Willingness to pay for existence or bequest value

Figure 2: The multiple ecosystem goods and services affected by water quality and quantity. For each benefit we list the biophysical changes that impact costs and benefits, the location and groups of beneficiaries affected by changes, and the economic approaches used to value each change. Table adapted from Keeler et al. 2012.

Summary Budget Information for Activity 3:	**ENRTF Budget:**	**$ 62,978**
	Amount Spent:	**$ 62,978**
	Balance:	**$ 0**

Outcome	Completion Date
1. Statewide inventory of water-related costs and benefits.	*Winter 2016*
2. Spatially-explicit economic values for changes in water quality and quantity based on alternative future scenarios developed in Activities #1-2.	*Summer 2017*

Activity Status as of*:* January 2016
Dr. Keeler and a Research Assistant supported by the project began work collecting and interpreting data on the economic value of water resources in Minnesota, with a focus on water quality data. The data will be used to estimate the distribution of potential future costs and benefits of changes in water quality on recreation, treatment costs, and human health. Work was also initiated on developing economic valuation functions for changes in water quality that incorporate supply and demand for water resources.

Activity Status as of: July 2016
Dr. Keeler and Research Assistants assembled data on the relationship between chronic, low-dose nitrate exposure through drinking water contamination and cancer risk. This data will contribute to a Monte Carlo simulation and uncertainty analysis that will inform the comprehensive economic valuation of water quality for the state. Pairing the possible public health risks of nitrate exposure with spatially-explicit data on well contamination will give insight into potential risks under future scenarios of agricultural development and remediation efforts. The team also assembled relevant state-wide datasets and spatially explicit metrics that will be integrated with the water scarcity assessments completed in Activities 1 and 2.

Activity Status as of: January 2017
Work on economic analysis of water benefits has been put on hold until the climate data and Agro-IBIS modeling is complete. Work on beneficiaries mapping and economic valuation is expected to ramp up in the coming weeks.

Activity Status as of: July 2017 We have completed collection of spatial data on sediment impacts and costs, including data on bridge scour, dredging, and recreational impacts. This included data requests and interviews with Army Corps of Engineers and data collection for other sediment-impacted industries and activities. These data were assembled into a GIS and visualized. In addition, we completed a literature review of sediment impacts that is summarized in an annotated bibliography. We also collected data on drinking water supply management areas (DWSMA), including geologic and soils data, water treatment methodologies and costs, and population and demographic data. Insights from the sourcewater data were visualized in a GIS and also submitted as a GIS “story map” and essay in the open access journal “Open Rivers” for publication this fall.

Activity Status as of: January 2018
Dr. Keeler’s team has completed the collection of spatial data on water-related ecosystem services, including lake recreation, groundwater nitrate, and freshwater angling. Researchers on the project have successfully converted outputs from the IBIS model into raster inputs that can be combined with ecosystem services metrics and maps. Plans for data dissemination and visualization have been developed, along with ideas for peer-reviewed publications.

In summary, outcome #1 is largely complete and will be summarized in the final report. Data supporting outcome #2 have been collected as well and will be integrated into maps and other visualizations when the climate data and water scarcity maps are complete.

Activity Status as of: March 2019
We have developed a user survey to help guide the development and packaging of the climate and hydrologic data being developed. This survey also helps identify the extent to which future weather and climate patterns enter into user's current decision making. This will help us develop economic value measures tailored to user's interests. We have also developed a set of scenarios that will allow us to compare the additive effects on water depletion of climate, population growth, agricultural expansion, and technological improvements.

Final Report Summary:
This project represented a massive data processing and analysis workflow that produced hundreds of maps representing the best available projections of climate change in Minnesota. We have engaged in extra outreach efforts to ensure the data we produce match the needs of communities and practitioners in Minnesota. In producing and disseminating this full suite of public climate data, we allocated less effort to monetary valuation of water related services. Given the uncertainty inherent in making both water use assumptions and climate projections at the end of the century, we opted to focus our efforts on creating robust estimates of precipitation (and other climate variables) and linking that to realistic scenarios of future consumption**.** We identified areas in the state where water consumption was high relative to precipitation, but did not find the water depletion at the annual scale even in high use watersheds. Locally, wells will influence the surrounding water table, but the amount of precipitation is not projected to decrease annually. *Thus, communities need to manage changing timing and intensity of precipitation, but not less overall*.

To quantify the impacts to people and industry we examined the economic impact of climate change through crop yields, and mapped the amount of additional precipitation communities should expect in increasingly intense events. Almost all of our corn yield projections indicated a 5-25% reduction in yield, with the largest and most widespread losses occurring in the mid-century projections. Soy yield also declined 5-25% in the mid-century projections, but southwestern and northwestern regions saw increased soy yields in the high emissions end of century scenario. We found increases in the intensity of rain events as measured by the size of annual average largest 5-day rainfall totals statewide. The increases for this measure were particularly severe along the north shore. By the end of the century, north shore communities are projected to have 50% more precipitation in the annual average largest 5-day total, thus stressing local infrastructure. The combination of our high spatial and temporal resolution of our projections and our derived data products designed to capture impact in terms relevant to a broad audience; we have provided local planners in Minnesota with an unparalleled new tool for making prudent decisions in the face of a changing climate.

This research has produced two significant outcomes for policy and management in Minnesota. First, the accompanying final report provides a high level, accessible overview of our projections for Minnesota's climate. The themes we selected highlight impacts to agriculture, recreation, groundwater, and human wellbeing at a local level throughout the state. We will continue to feature these results in presentations and other communications with practitioners. Second, once they have gone through peer-review, we will be sharing our climate and water balance modeling outputs. This includes typical climate variables such as temperature and precipitation, as well as those derived from further modeling, such as evapotranspiration and run off. We surveyed practitioners to inform the best way to disseminate these data, and as we continue to use and build off these outputs in other research, we will continue to update the data we share.

In completing this research, we identified topics in need of future research that would have informed the approaches we took. The mechanics of groundwater movement in the state proved to be a reoccurring source of uncertainty. This work would have benefitted from local modeling to check our assumptions when sufficient geologic data was available. Using the DNR's network of groundwater level monitoring wells would have been another useful case study comparison, though it lacks coverage and the ability to project into the future. We know that many researchers at state agencies and private engineering firms have the expertise and capacity to extend the groundwater modeling efforts we present here. Our projections of precipitation and water balance modeling will be an invaluable input to their work.

A second source of uncertainty in this project is future rate of groundwater withdrawal. We performed extensive analysis on DNR well permit data to forecast future withdrawals, but ultimately recognized that technology and irrigation adoption are major drivers that we do not have a reliable way to predict. While technology 80 years from now is inherently unpredictable, we are already performing research to better estimate irrigation practices under climate change. We are surveying producers in Iowa on their irrigation use and under what circumstances they would adopt irrigation. This research will be applied our climate projections to gain a better understanding of how the largest source of water consumption in Minnesota is likely to evolve.

V. DISSEMINATION:

Description: We expect the results of our work to be useful to the diverse groups of planners, regulators, agencies, and managers with an interest in water sustainability in Minnesota. We will make all data products and reports available to the LCCMR and complete all regular project reports. We will also collaborate with the Institute on the Environment's digital media platform ensia.com to create web- based resources to disseminate data and highlight key findings generated through project activities.

Project Status as of*:* January 2016
The project was highlighted in a recent blog post on the Institute on the Environment's website: http://environment.umn.edu/water/what-is-the-future-of-clean-water-in-minnesota/.
Project research on water use by sector was presented at the AGU Annual Meeting in San Francisco, CA https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/74042
Project updates were presented to the Clean Water Council in November, 2015 by Dr. Keeler and Dr. Polasky

Project Status as of: July 2016
No additional dissemination updates to report.

Project Status as of: January 2017
No additional dissemination updates to report.

Project Status as of: July 2017

Project Status as of: January 2018
Project updates were presented to the MN DNR at the DNR Science Forum on October 30th, 2017.

Project Status as of: March 2019
In an effort to both build awareness for our work and to solicit input on the most useful data formats, we created and administered a survey to approximately 100 practitioners who are likely to need high resolution projections of climate and water availability in the future. Our list included people in the private and non-profit sectors and extensive representation of state agencies. Our survey will give us insight into how the needs of practitioners so we can produce data products that are most useful to them. The survey also provided respondents with an opportunity to be notified when the data are being distributed, giving us a list of users who are ready to use the research once it is complete.

In addition, Minnesota Daily published a news article describing our work downscaling climate change data and its importance to understand how future climate change may impact the state's water resources. The article is available via https://www.mndaily.com/article/2019/03/n-umn-researchers-examine-how-climate-change-affects-states-water

Final Report Summary:

Given the relevance of reliable, high-resolution projections of future climate to audiences making a broad range of critical management and planning decisions, we took extra dissemination steps to ensure our research is accessible and actionable.

We developed a survey to measure the demand for different formats of climate data products from users in the public, private, and non-profit sectors. A key insight from this outreach effort is the diversity of way our data products will be used. Across the public, private, and non-profit sectors, there was a mix of planning for infrastructure, ecological restoration, human health, and flooding impacts. Below are a sample of quotes from respondents. A summary of all the results from the survey are available in as an supplement to this report.

- "prioritize infrastructure projects that increase community resilience"
- "understanding how restoration activities can be prioritized to improve populations of various grassland wildlife and game species."
- "Projections of precipitation trends is assisting with emergency flood planning at our wastewater plant"
- "planning watershed restoration and protection strategies, identifying effective BMP's for restoration or protection"
- "developing a methodology for incorporating climate change considerations into asset management of bridges and culverts"
- "Better understanding the potential health impacts from more extreme weather events."
- "Tree species selection and recommendation for community forests"

We also learned from this survey of practitioners what data formats and variables would be most applicable to their work flows. For example, compared to more processed data products, respondents preferred absolute measures at monthly intervals with no spatial aggregation. Although these are more challenging to disseminate due to their size and complexity, we are making more variables available in this way in response to user demand.

The survey effort has also helped us identify who potential users of climate change projections are throughout the state. Respondents were encouraged to share the survey with colleagues working on the topic and all respondents had the opportunity to opt into notifications about future data dissemination efforts.

In addition to surveying potential users, we also reached out to the state climatologist, Kenny Blumenfeld, for recommendations on how to capture the frequency and impact of extreme weather impacts in a way that is more accessible to a broad audience. For example, instead of only reporting the average maximum temperature in each month, we are producing a map of the change in number of days each year projected to be above 95F. While the former is more traditional in academic research, the latter quickly conveys an impact in relatable terms.

The climate change projections produced under this research will be made available in two phases. In the first phase, individuals interested in working with the data will be able to contact Tracy Twine in order to obtain a copy of the datasets, in the second phase the data will be posted to a public web server. The first phase will allow us to better understand the users of the data, and to provide support when it is unclear what is represented. In this time, we will publish a peer-reviewed manuscript detailing the production of the data. It is standard practice in this and many other fields to not release underlying data products until they have been peer-reviewed and published. User feedback will also inform any clarifications we make before posting the data to a publicly accessible web server. When the data are posted publicly, this URL will permanently direct users to that server: https://z.umn.edu/climate-change-data. Prior to that, they are available upon request by emailing Tracy Twine at twine@umn.edu.

For the scientific audience, we plan for several peer-reviewed publications to use this research as a foundation, and the work will also be presented during at least one scientific conference. To make these scientific data sets relevant to all Minnesotans, we are also working with the professional communication teams at the University of Minnesota to publish a short, accessible blog post describing our methods and highlighting the most relevant findings to the general public. We will time the release of this post around the public posting of the data to leverage further coverage into highlighting the public availability of the data.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 234,000	Funding is requested to support time for the three lead investigators (Twine- 1 month for 1 yr at $12,375, Brauman- 2 months for 2 years at $34,891, Keeler- 3 months for 2 years at $46,372) to supervise the project and lead research activities. Two full-time staff will support the work and report to the lead investigators. One full-time, 12 month appointment for a Post-doctoral Research Associate in the Department of Soil, Water, and Climate. This individual will generate new down-scaled climate data and parameterize and run the Agro-IBIS model to support Activity #1. Estimated cost: $60,375. One full-time, 16.5 month appointment for an Assistant Scientist to be based at the Institute on the Environment. This individual will assist with spatial data management, mapping and analysis, and new data collection to support proposed Activities #1-3. Estimated cost: $79,584.
TOTAL ENRTF BUDGET:	**$234,000**	

Explanation of Use of Classified Staff:

Explanation of Capital Expenditures Greater Than $5,000:

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 3.3 FTE's

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:

B. Other Funds: N/A

VII. PROJECT STRATEGY:

A. Project Partners: N/A

B. Project Impact and Long-term Strategy:

The proposed work will deliver valuable information on the status, trends, and future condition of one of the state's most valuable resources. The project leverages existing state data and cutting-edge research and models to create new spatial maps and tools that will support more informed water management. The outcomes of the work will identify current problem areas, major threats to water sustainability by region, and potential risks to different sectors that rely on clean water. In addition, the project will provide in-demand information on the value of clean water – information that can be used in cost-benefit assessments, permitting decisions, and more informed analyses of tradeoffs. This project is a stand-alone effort and not part of a longer-term funding request, although it builds and expands on model development and applications in Minnesota and globally.

C. Funding History: N/A

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS:

N/A

IX. VISUAL COMPONENT or MAP(S):

See attached visual component.

X. RESEARCH ADDENDUM:

See attached research addendum.

XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than January 2016, July 2016, January 2017, July 2017, and January 2018. A final report and associated products will be submitted by June 30, 2018.

Environment and Natural Resources Trust Fund
M.L. 2015 Project Budget

Project Title: Understanding Water Scarcity, Threats, and Values to Improve Management
Legal Citation: *M.L. 2015, Chp. 76, Sec. 2, Subd. 04a - as extended M.L. 2018, Chapter 214, Article 4, Section 2, Subdivision 20*
Project Manager: Bonnie Keeler
Organization: University of Minnesota **00043131** **Through 3/14/19**
M.L. 2015 ENRTF Appropriation: **$** 234,000
Project Length and Completion Date: June 30, 2019
Date of Report: March 14, 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	***Water modeling***			***Water risks and scarcity assessment***			***Water valuation***				
Personnel (Wages and Benefits) Overall	$73,153	$73,153	$0	$97,869	$97,869	$0	$62,978	$62,978	$0	$234,000	$0
Personnel: Full-time, 12 month appointment for a Post-doctoral Research Associate in the Department of Soil, Water, and Climate. This individual will generate new down-scaled climate data and parameterize and run the Agro-IBIS model to support Activity #1. Salary is $50,000 plus $10,375 fringe (20.75%). Estimated total $60, 375		55,288			947						
Personnel: One-month salary equivalent for **Dr. Twine** to supervise the Agro-IBIS modeling and mentor the Post-docoral Associate. One month salary is $9,644 plus $3,134 for fringe benefits (32.5%). Estimated total $12,778.		12,865			-			-			
Personnel: Two-month salary equivalent, in each of the two project years for **Dr. Brauman** to complete the water scarcity analysis and risk assessments described in Activities #1-2. One month salary is $6,583 plus $2,140 for fringe benefits (32.5%). Estimated total $34,891.		-			28,450			7,655			
Personnel: Full-time, 16.5 month appointment for an Assistant Scientist to be based at the Institute on the Environment. This individual will assist with spatial data management, mapping and analysis, and new data collection to support proposed Activities #1-3. Annual salary is $43,000 per year plus $14,706 fringe (34.2%). Estimated total $79,584. Note that appointment length was reducedfrom the original proposal to accomodate for LCCMR-approved budget allocation.		-			44,130			37,345			
Personnel: Three-month salary equivalent, in each of the two project years for **Dr. Keeler** to complete the water quality risk assessment and water valuation work described in Activities #2-3. In addition, Keeler will serve as project manager, supervise the Assistant Scientist, and coordinate project activities and data dissemination. One month salary is $5,833 plus $1,896 for fringe benefits (32.5%). Estimated total $46,372.		5,000			24,342			17,978			
COLUMN TOTAL	**$73,153**	**$73,153**	**$0**	**$97,869**	**$97,869**	**$0**	**$62,978**	**$62,978**	**$0**	**$234,000**	**$0**

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September 15th, 2019

U of M Humphrey School of Public Affairs
Bonnie Keeler, Terin Mayer, Ryan Noe*, Margaret Rogers

U of M Department of Soil, Water, and Climate
Tracy Twine

U of M Institute on the Environment
Kate Brauman

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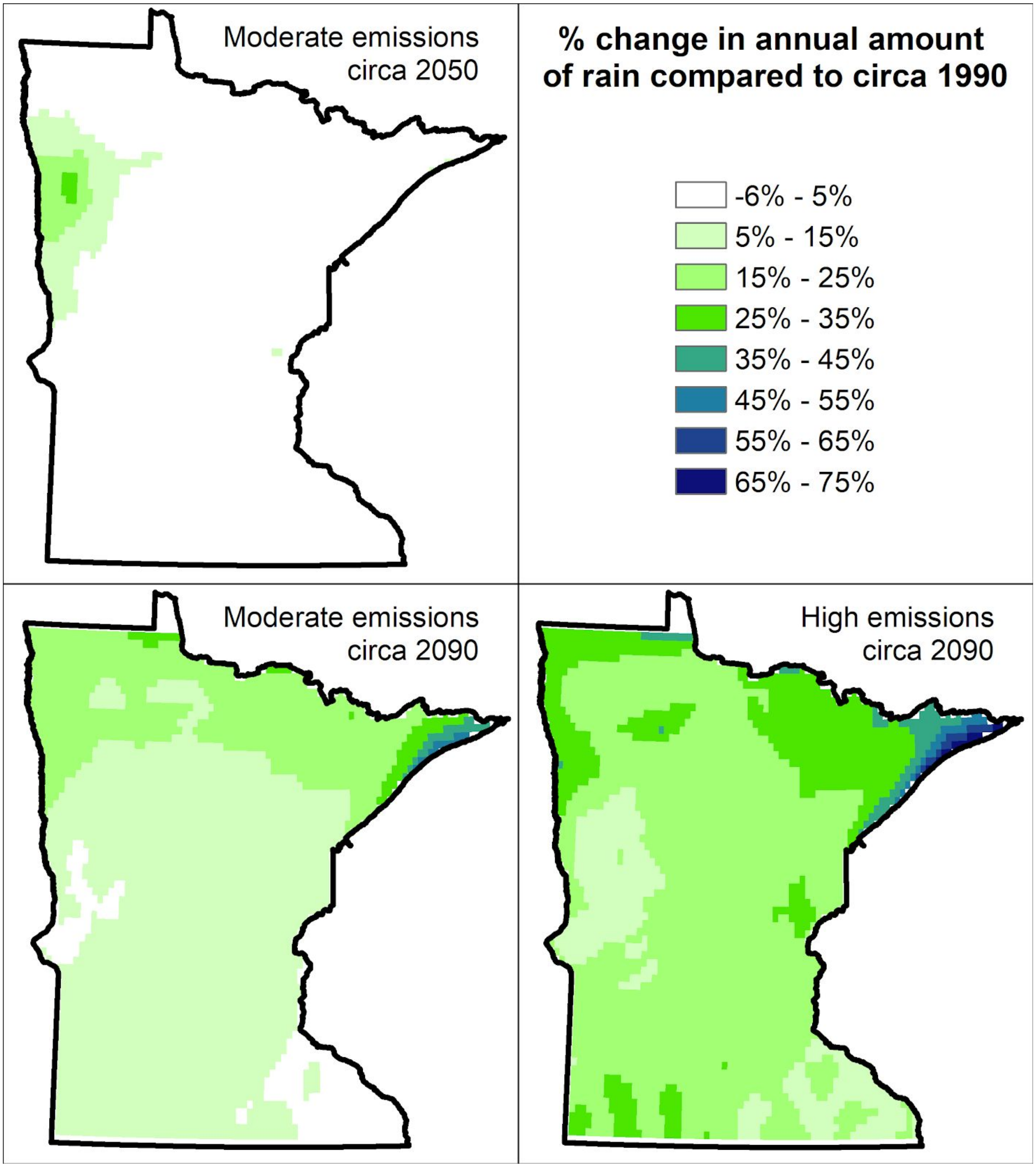

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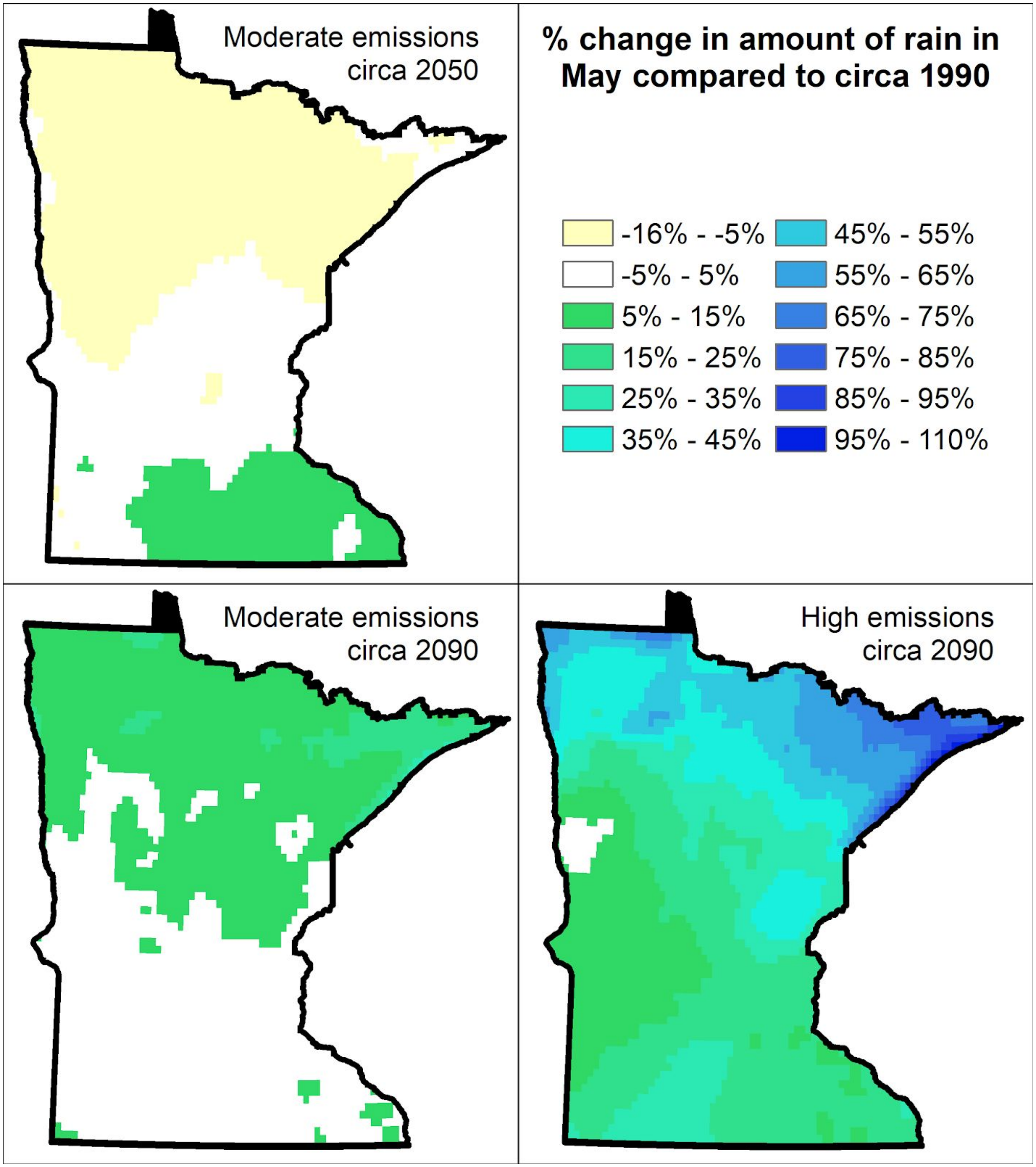

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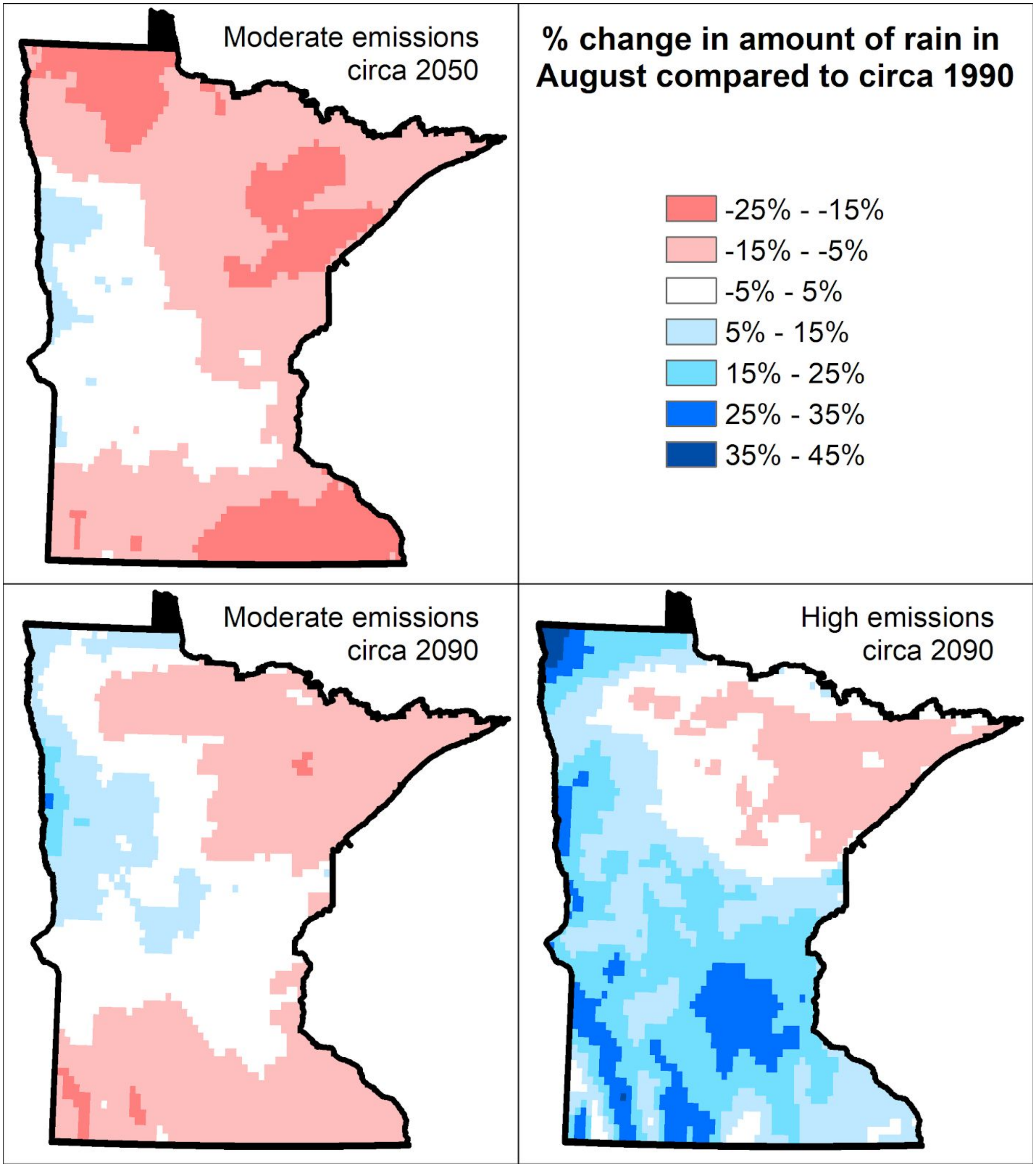

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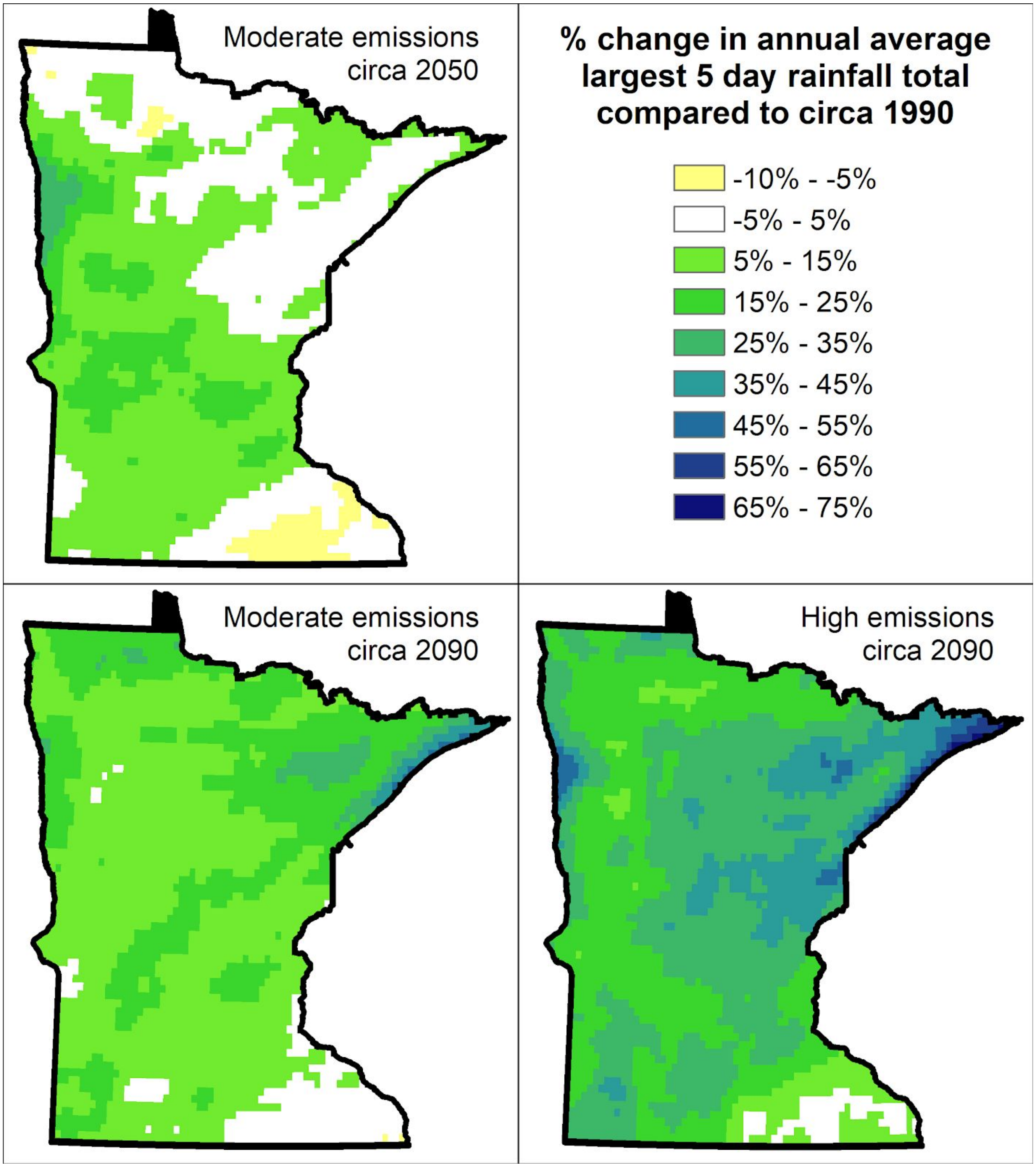

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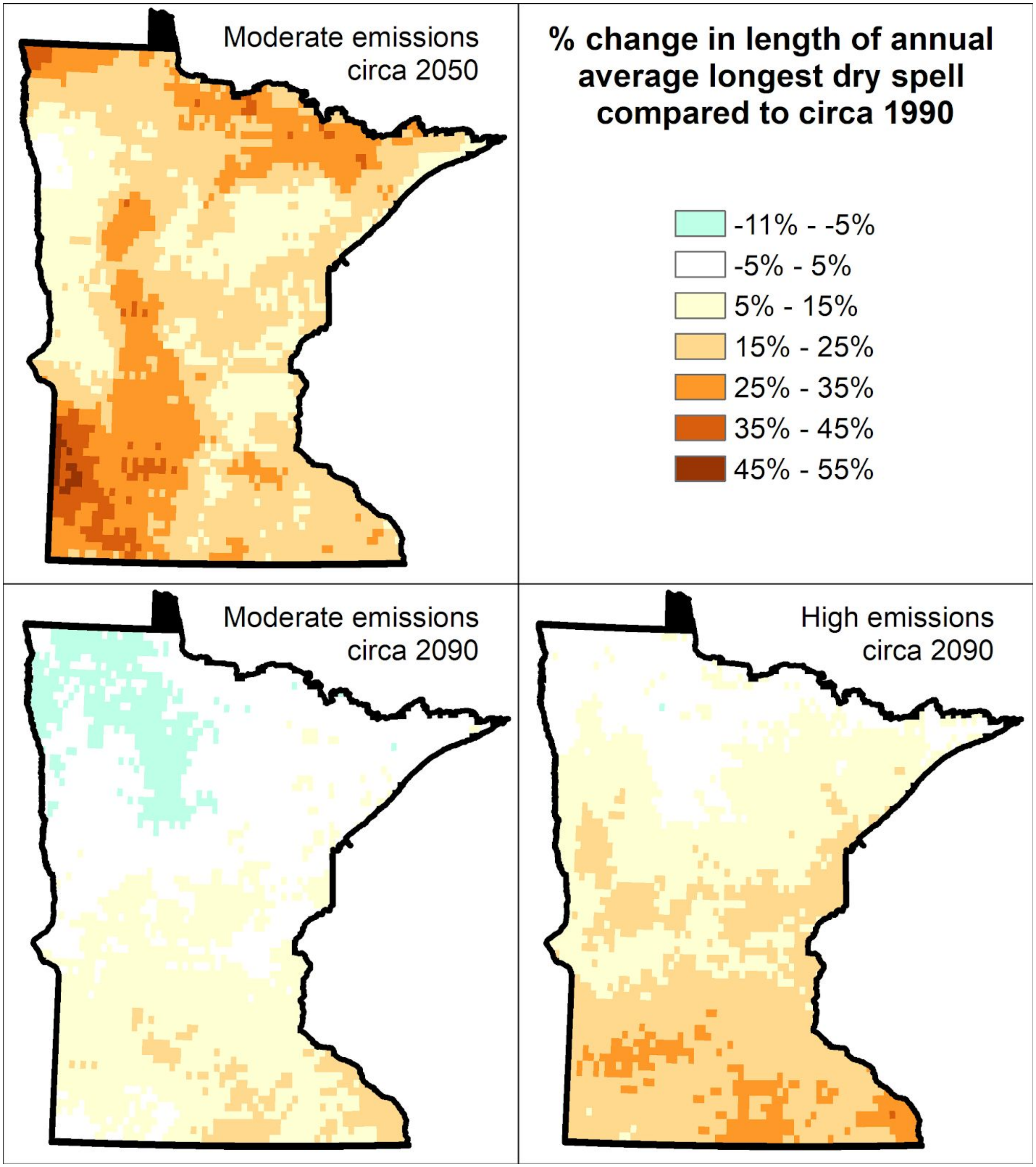

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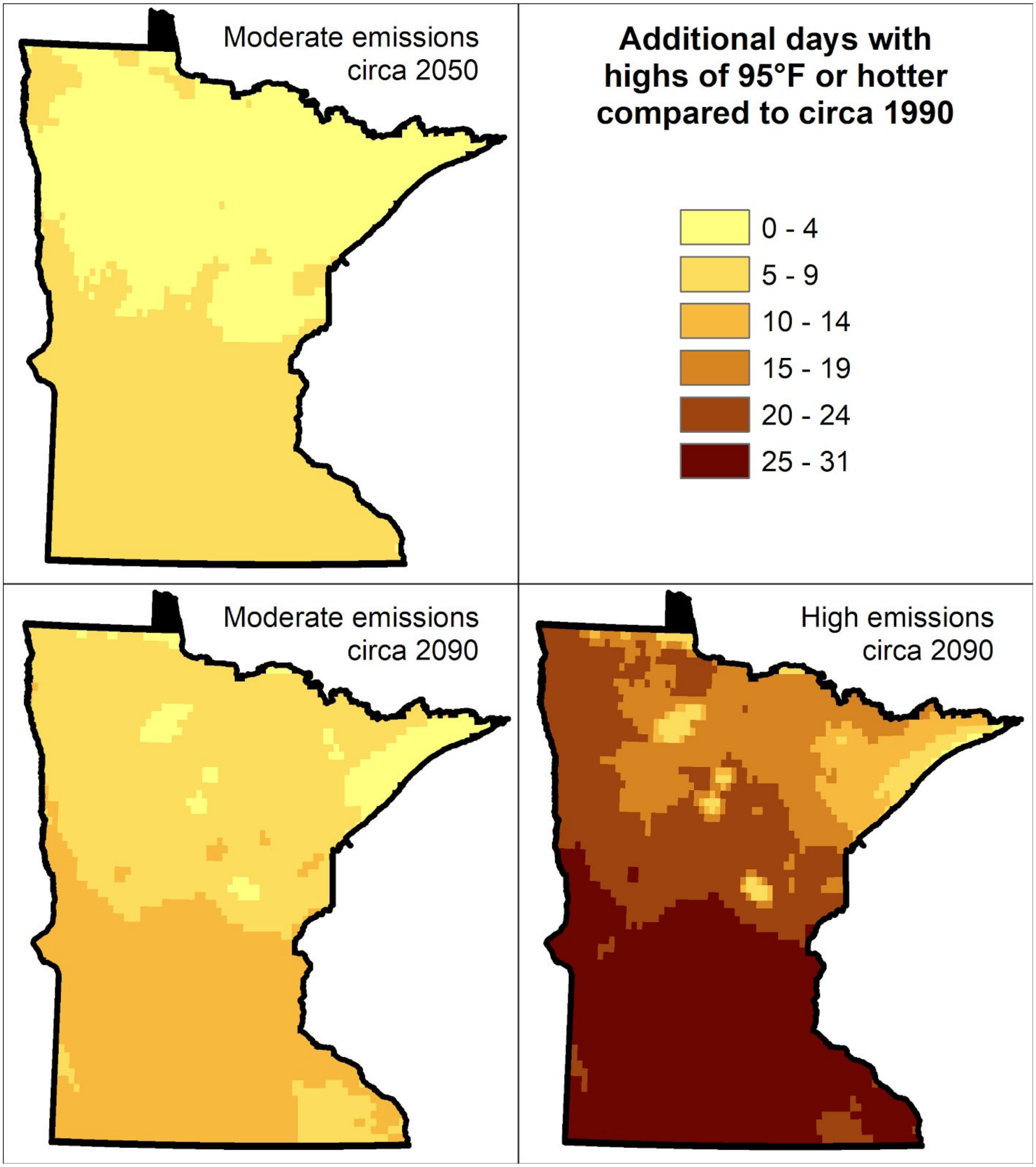

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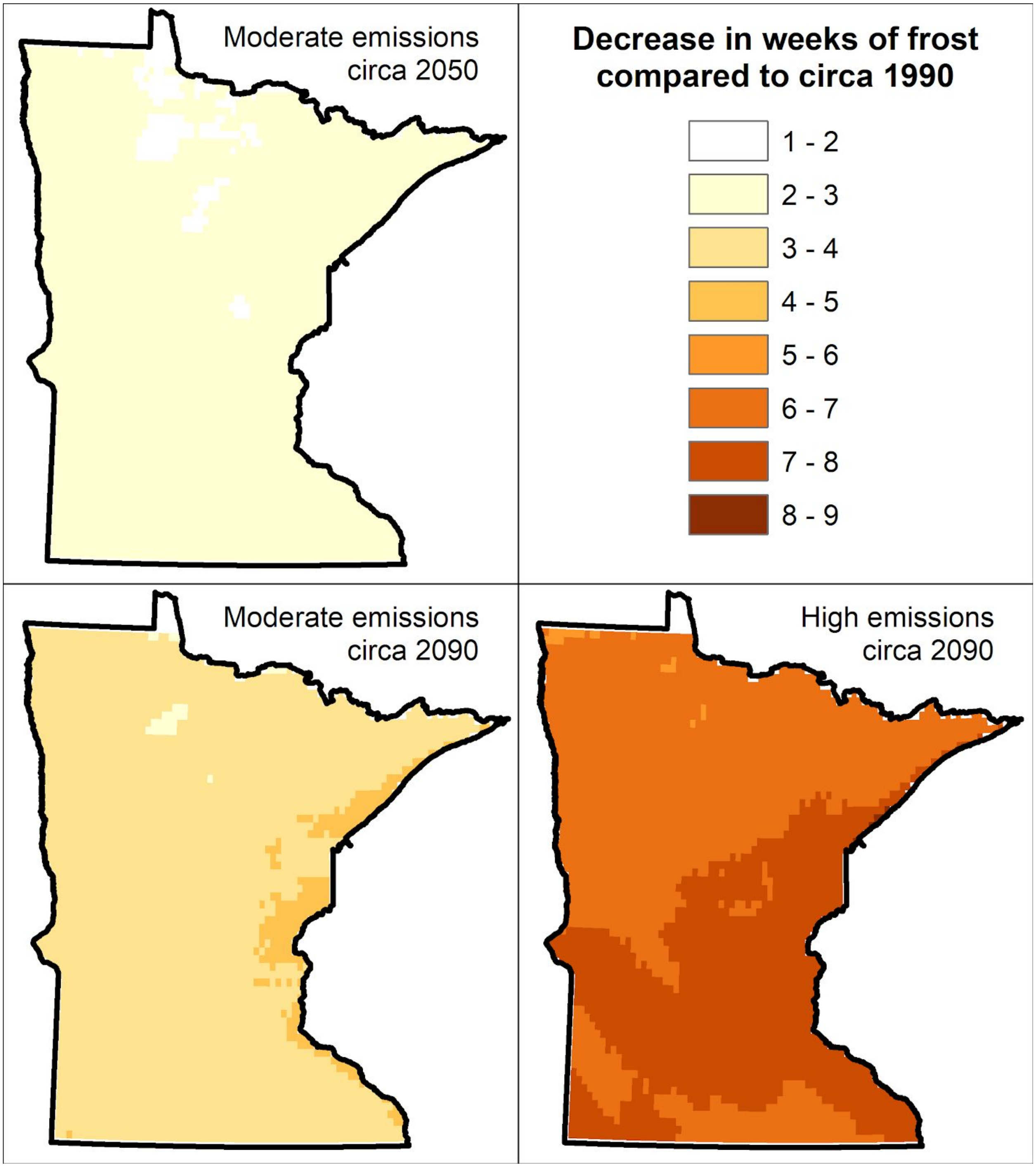

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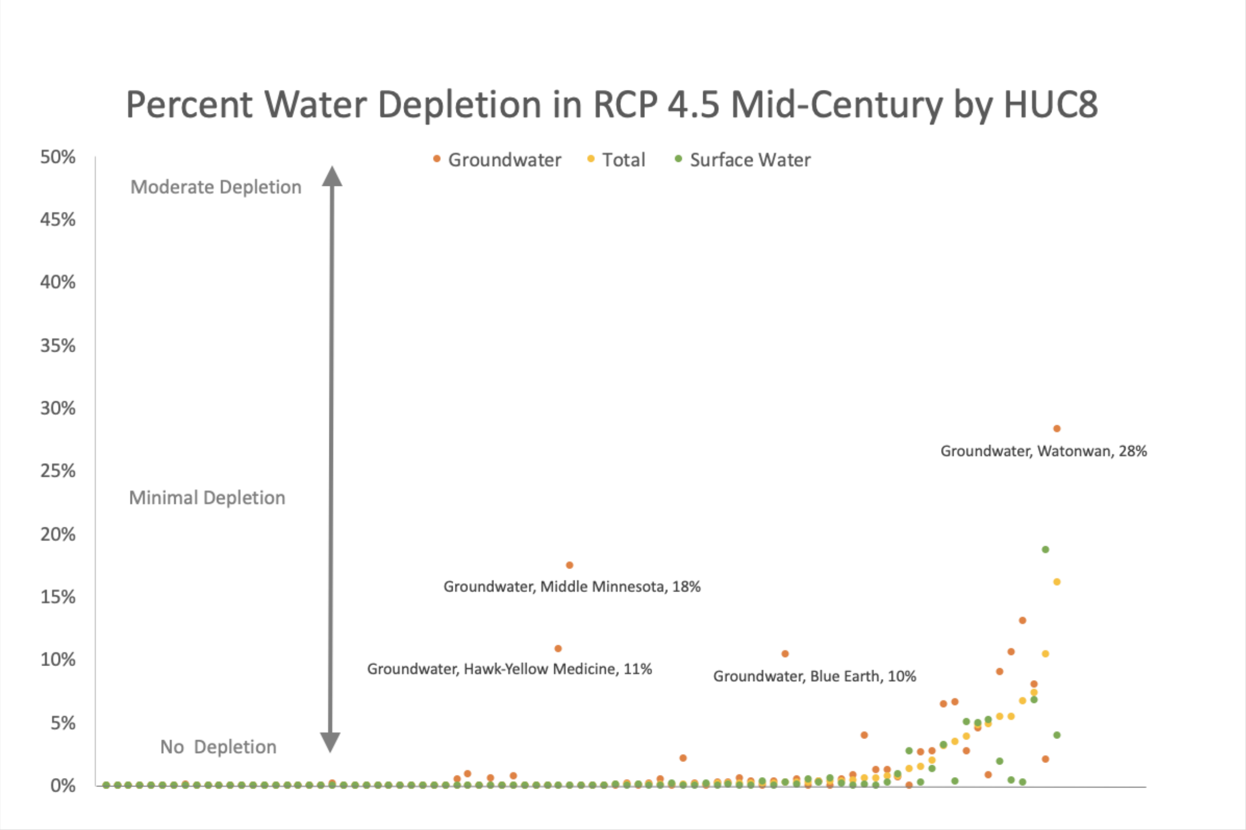

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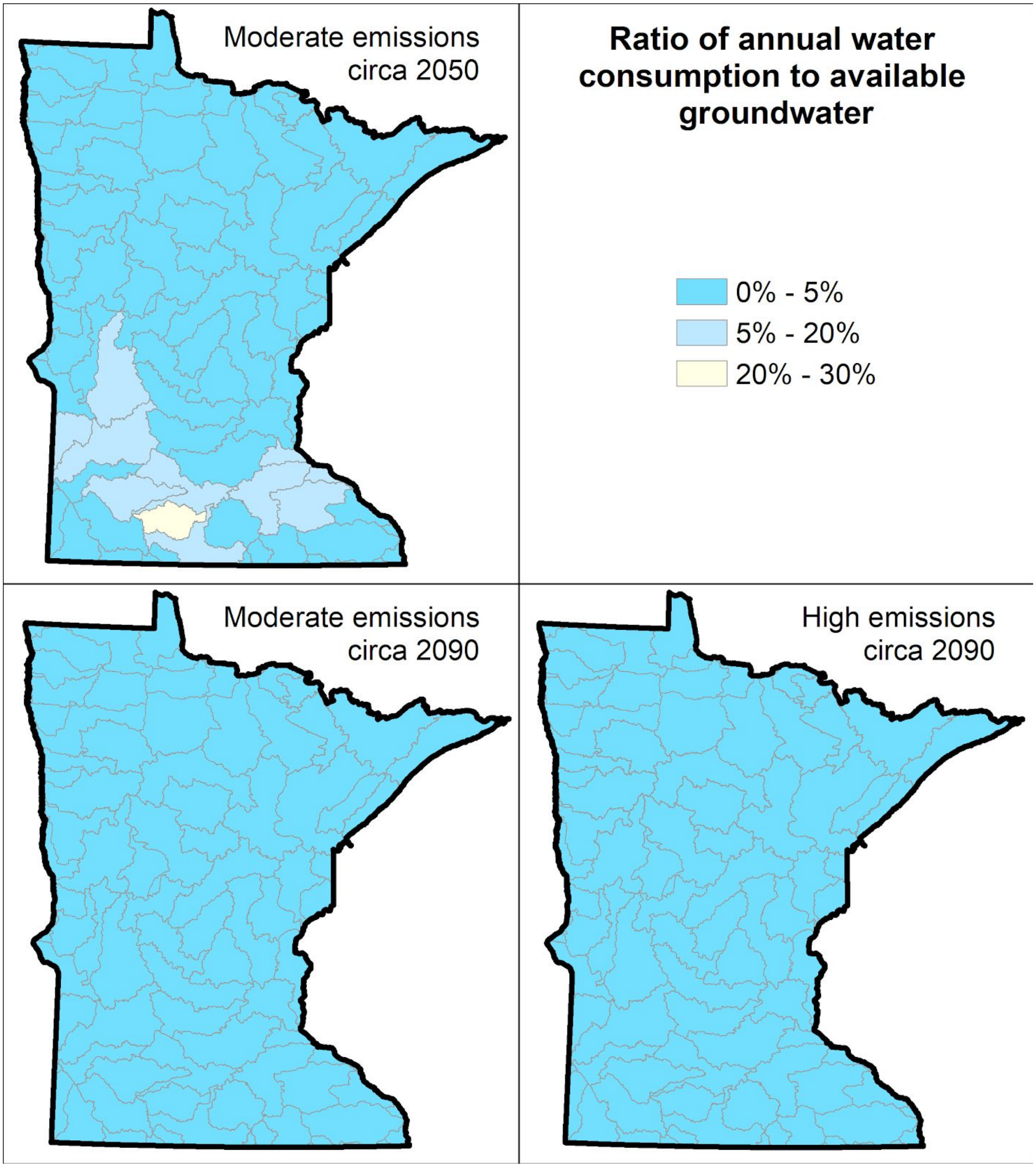

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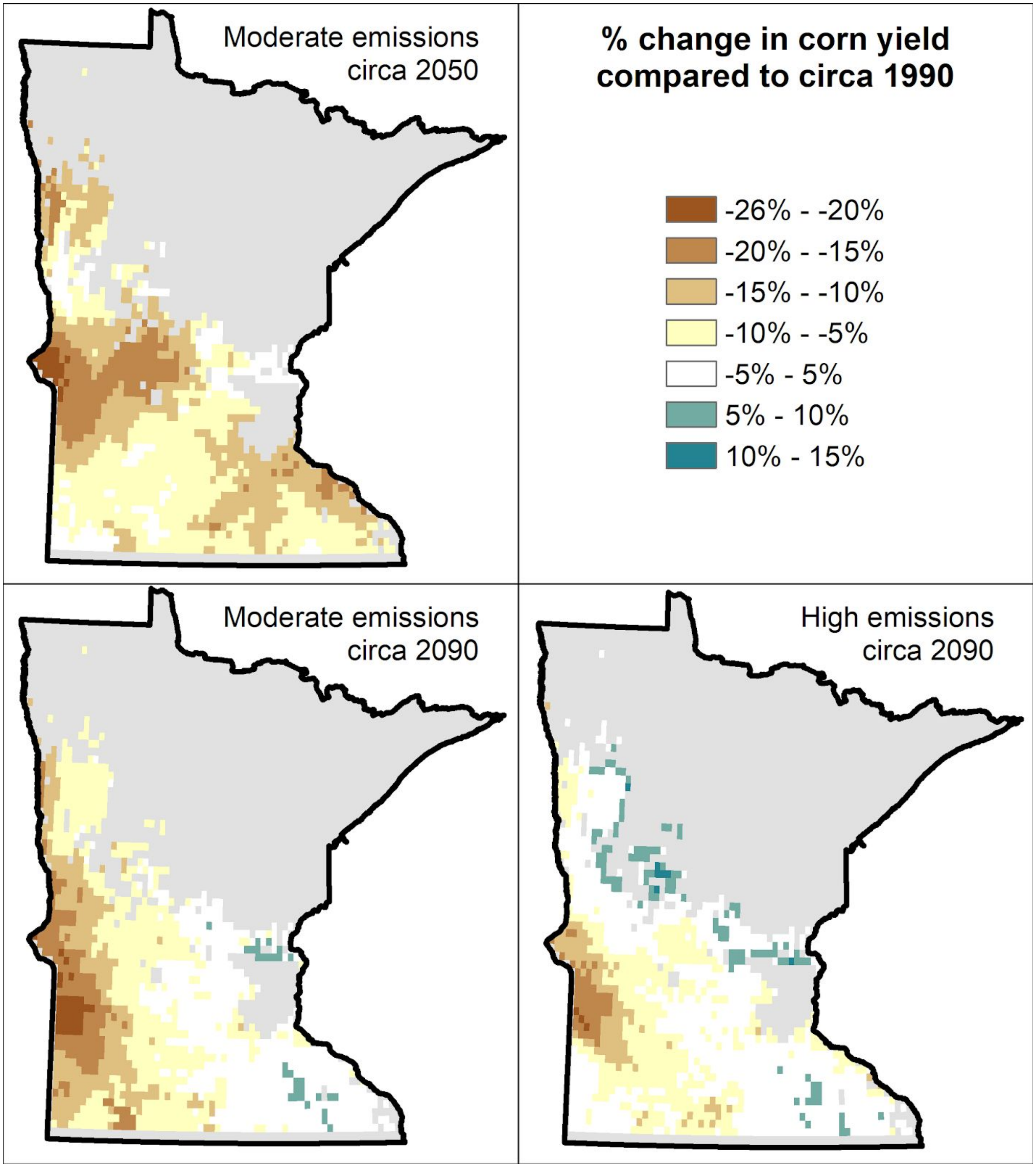

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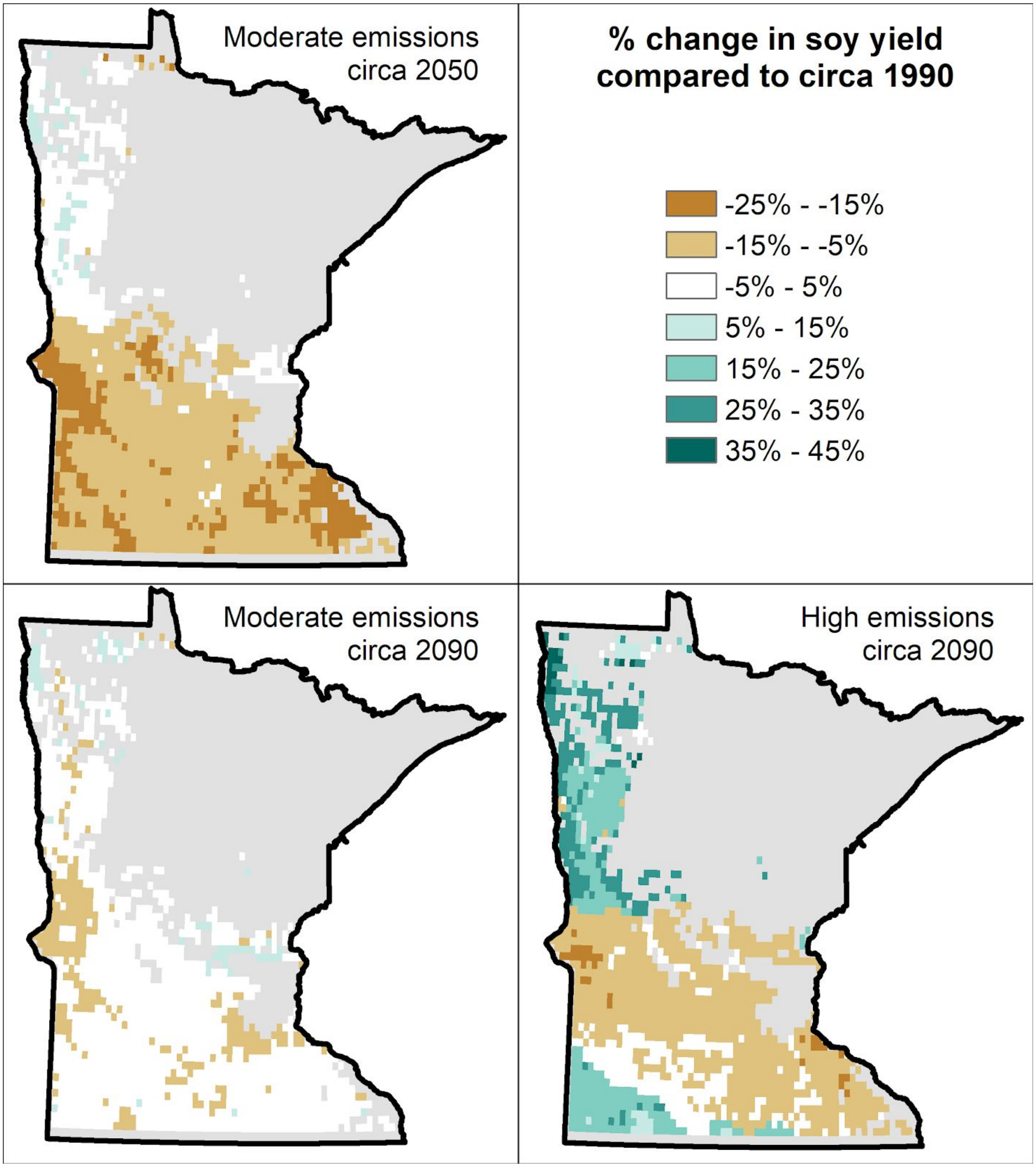

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Conclusions

From an annual average perspective, Minnesota is projected to be warmer with a consistent or greater quantity of precipitation relative to circa 1990. By dynamically downscaling global projections, we find that precipitation timing and intensity changes are likely. Although the annual quantity of precipitation will be similar or greater, we project similar or fewer days of precipitation and longer maximum dry spells. This results in more intense events that stress infrastructure and crop production. Corn yield declined in almost all regions and climate change scenarios, sometimes by as much as 25%. Warming trends will shorten winters, affecting winter recreation activities. In the summer, the state is projected to experience far more days with highs greater than or equal to 95°F.

With regards to water depletion, we did not find evidence for depletion annually. We found one watershed that had water consumption equivalent to 28% of its available groundwater in the mid-century period. This was the highest of any of the watersheds or scenarios analyzed, but is not extreme. Communities, especially those with elevated annual groundwater depletion, may have greater depletion on a short-term base and should consider surface water sources when expanding withdrawals. Our annual analysis is unable to detect short term depletion that could occur in response to longer dry spells under climate change. Our data products should be used in conjunction with models that include local geology to capture the influence of short term events on local features.

In an effort to provide tools for local communities to plan for climate change, we will make available the underlying data for this analysis after it has gone through the peer review process. Future updates can be found at https://z.umn.edu/climate-change-data.

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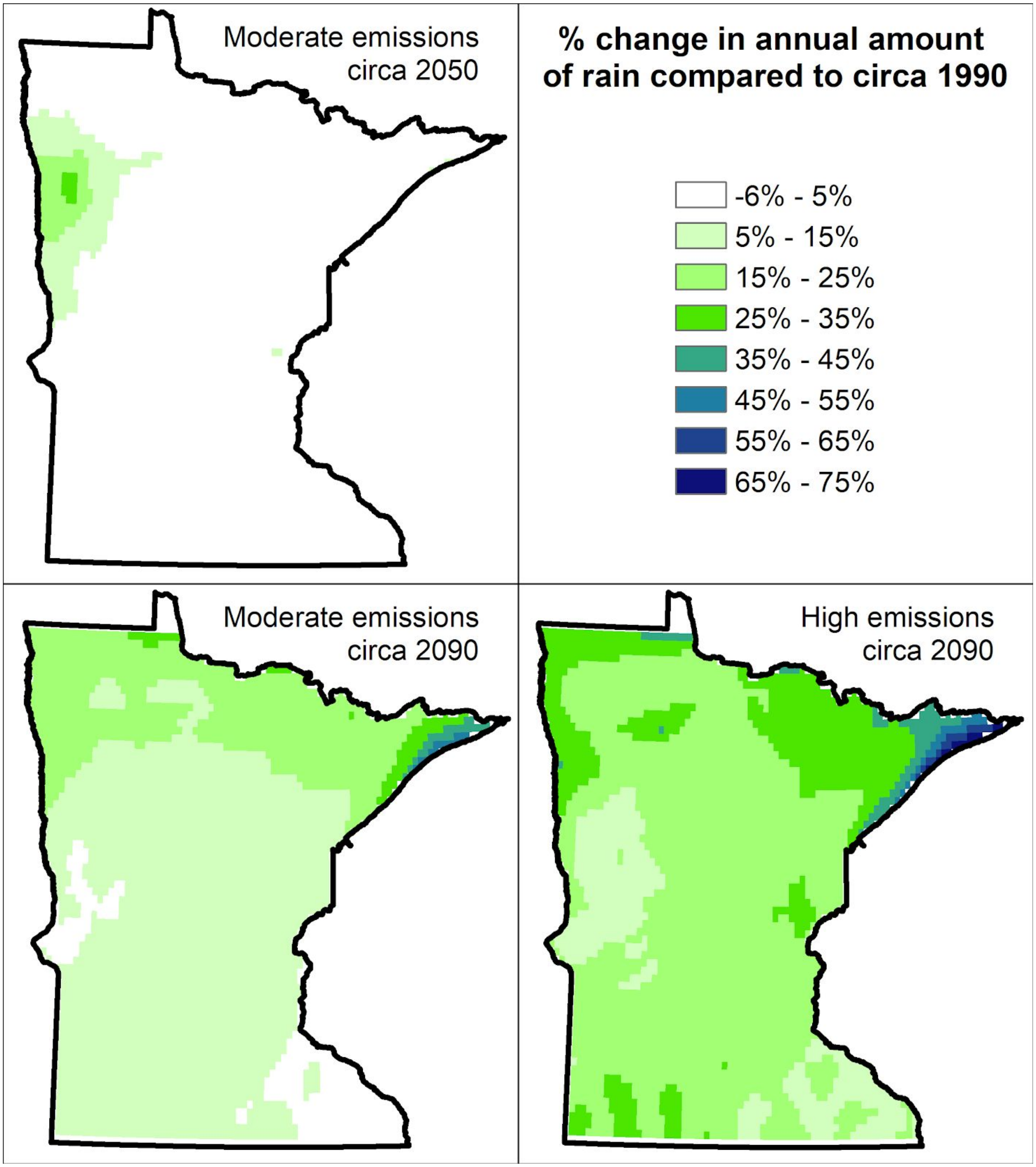

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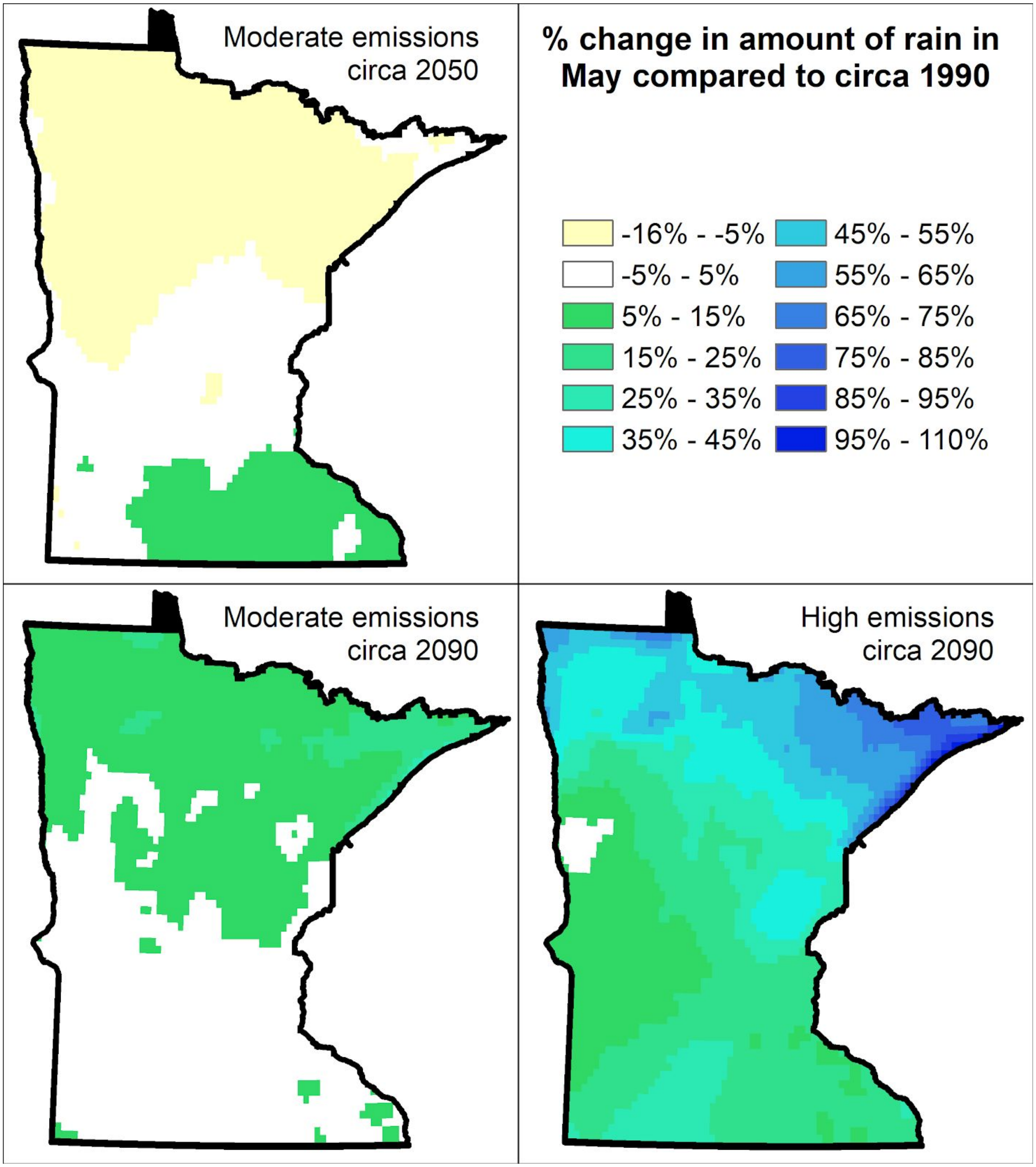

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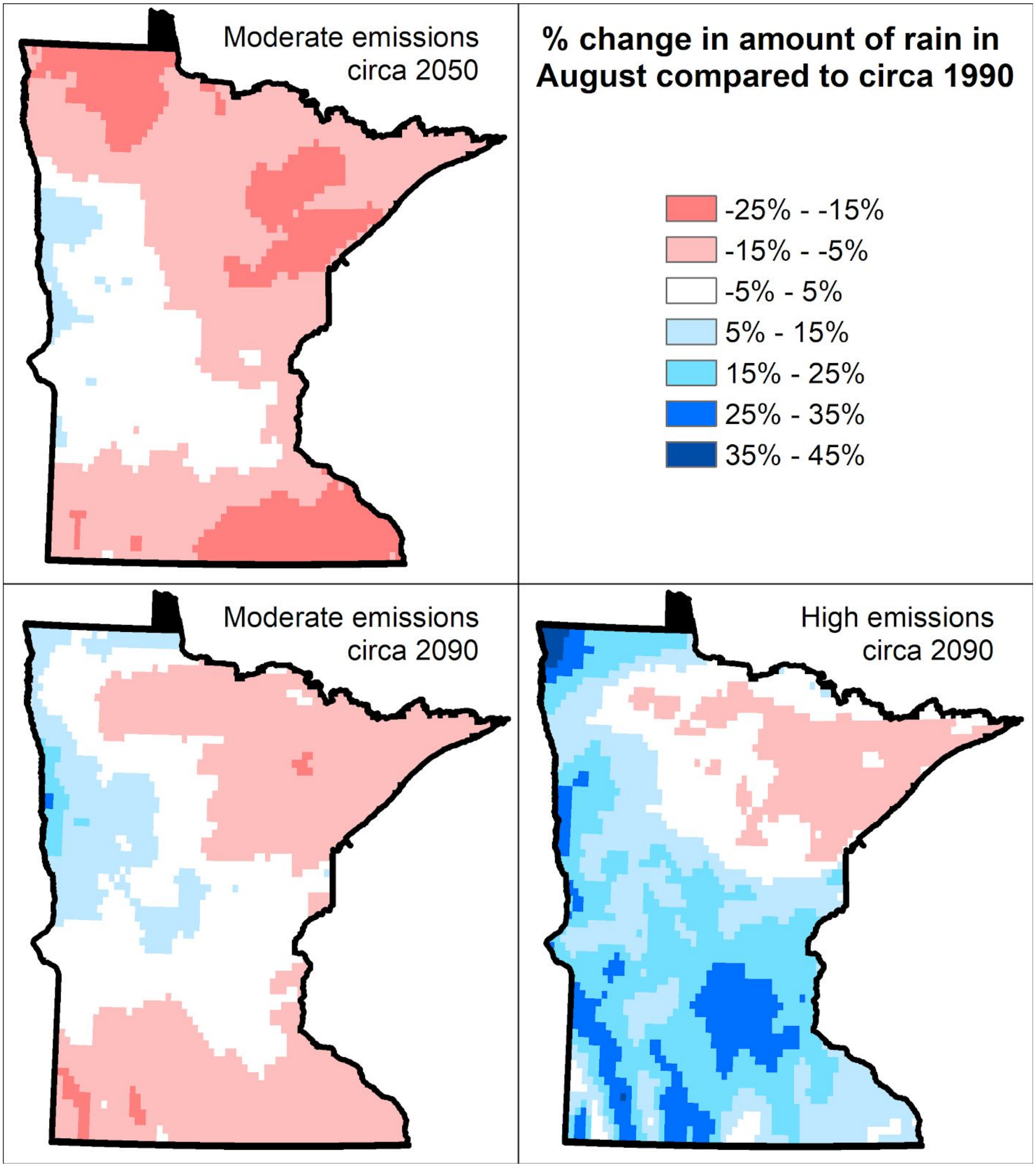

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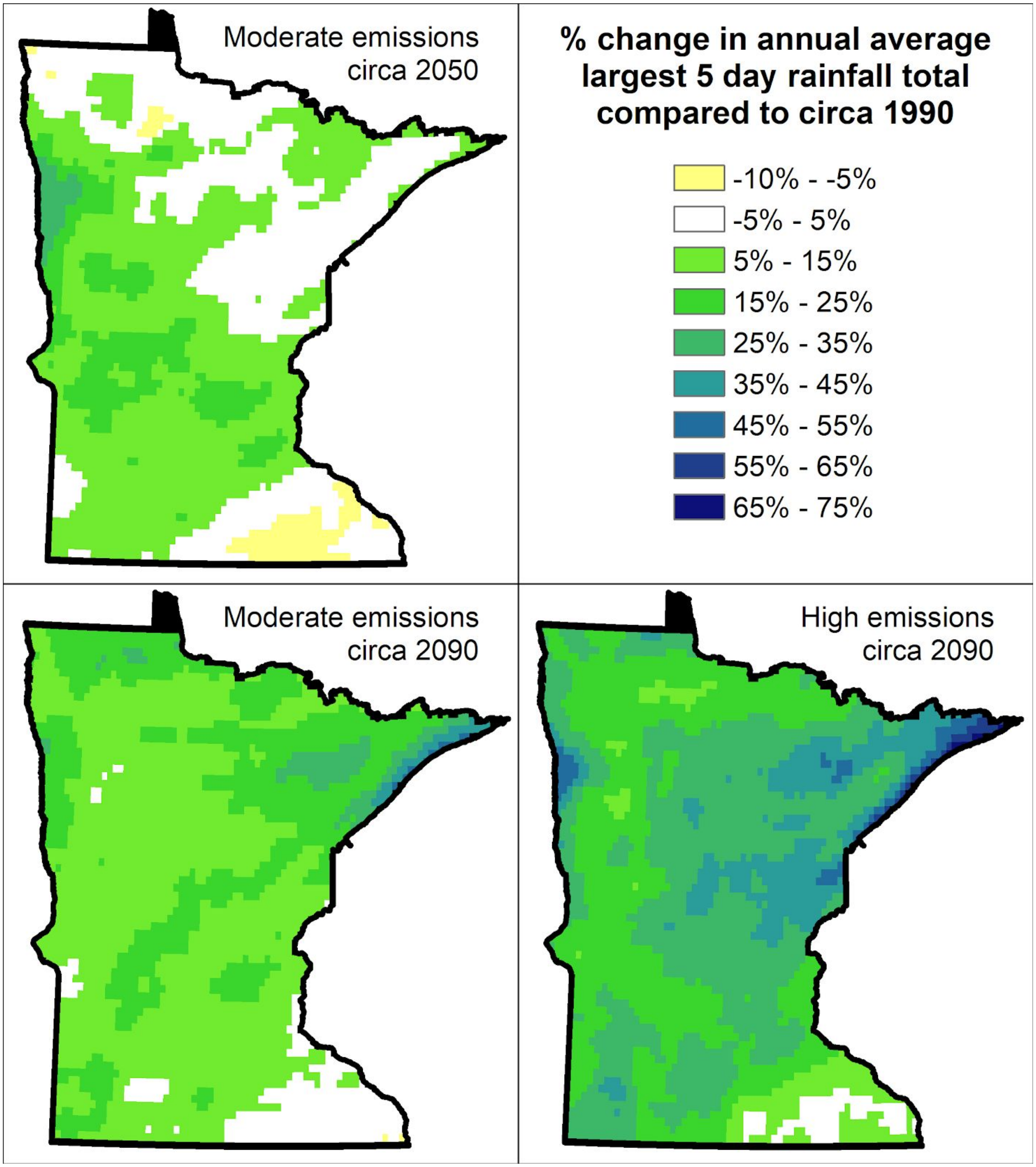

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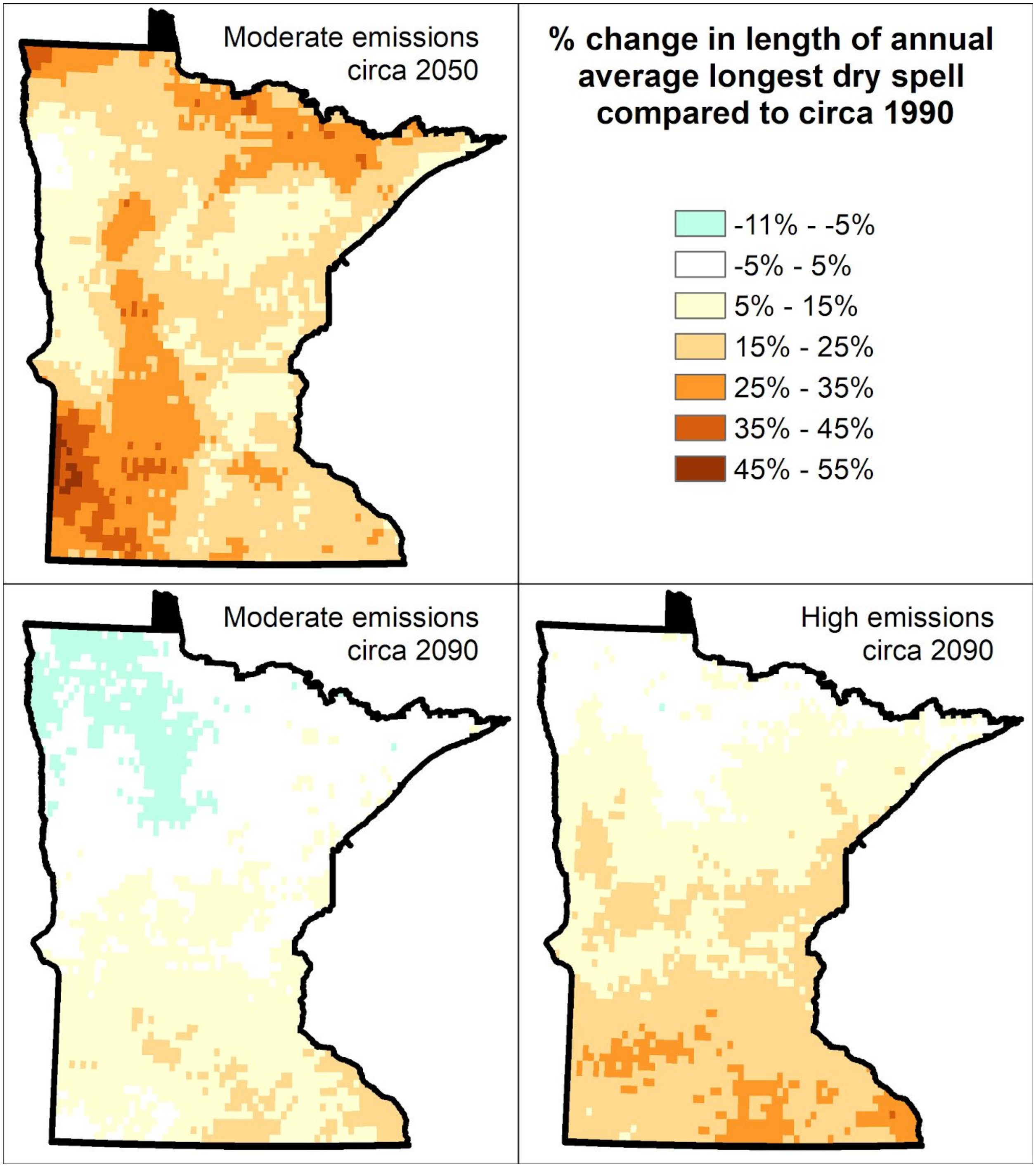

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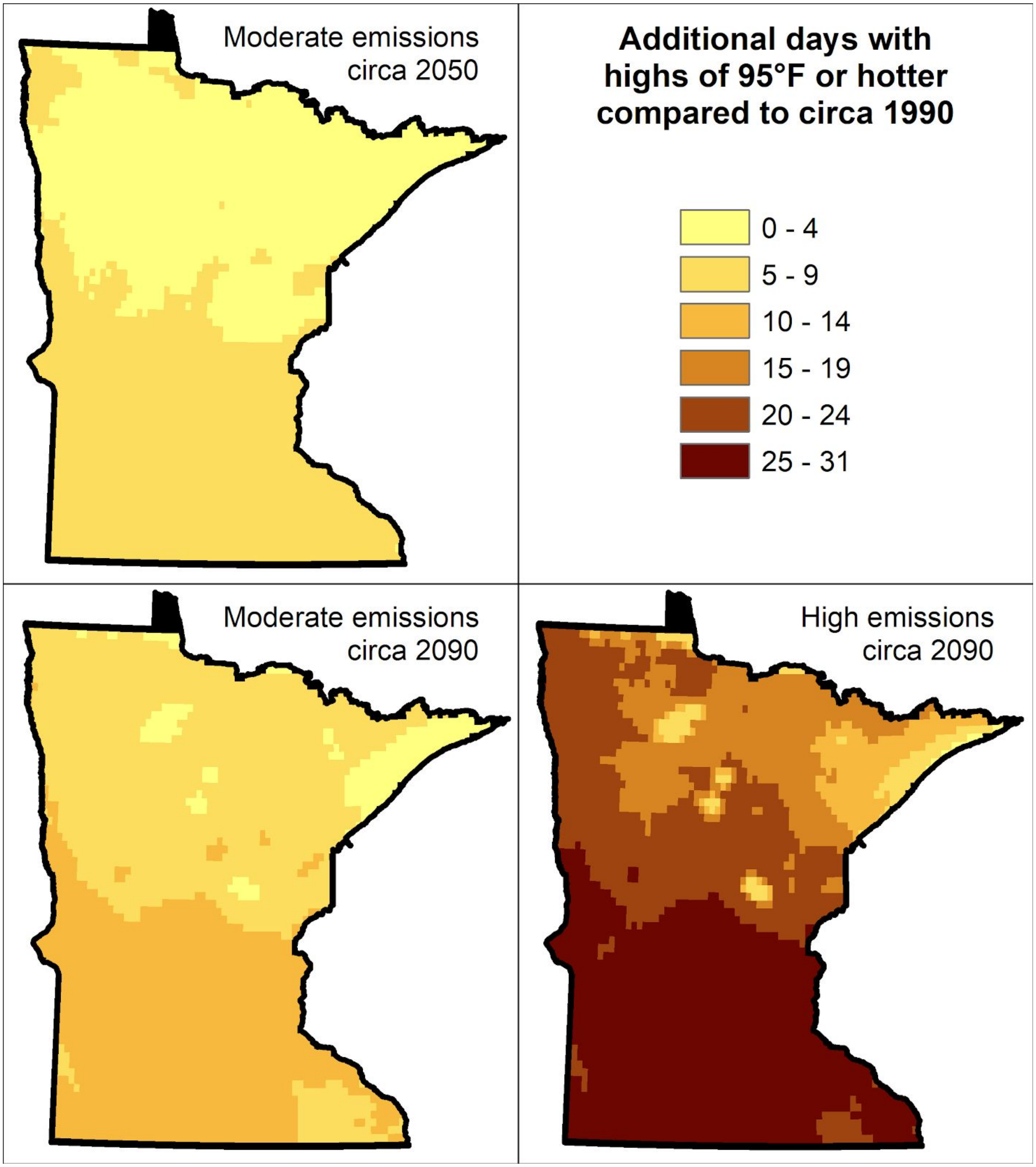

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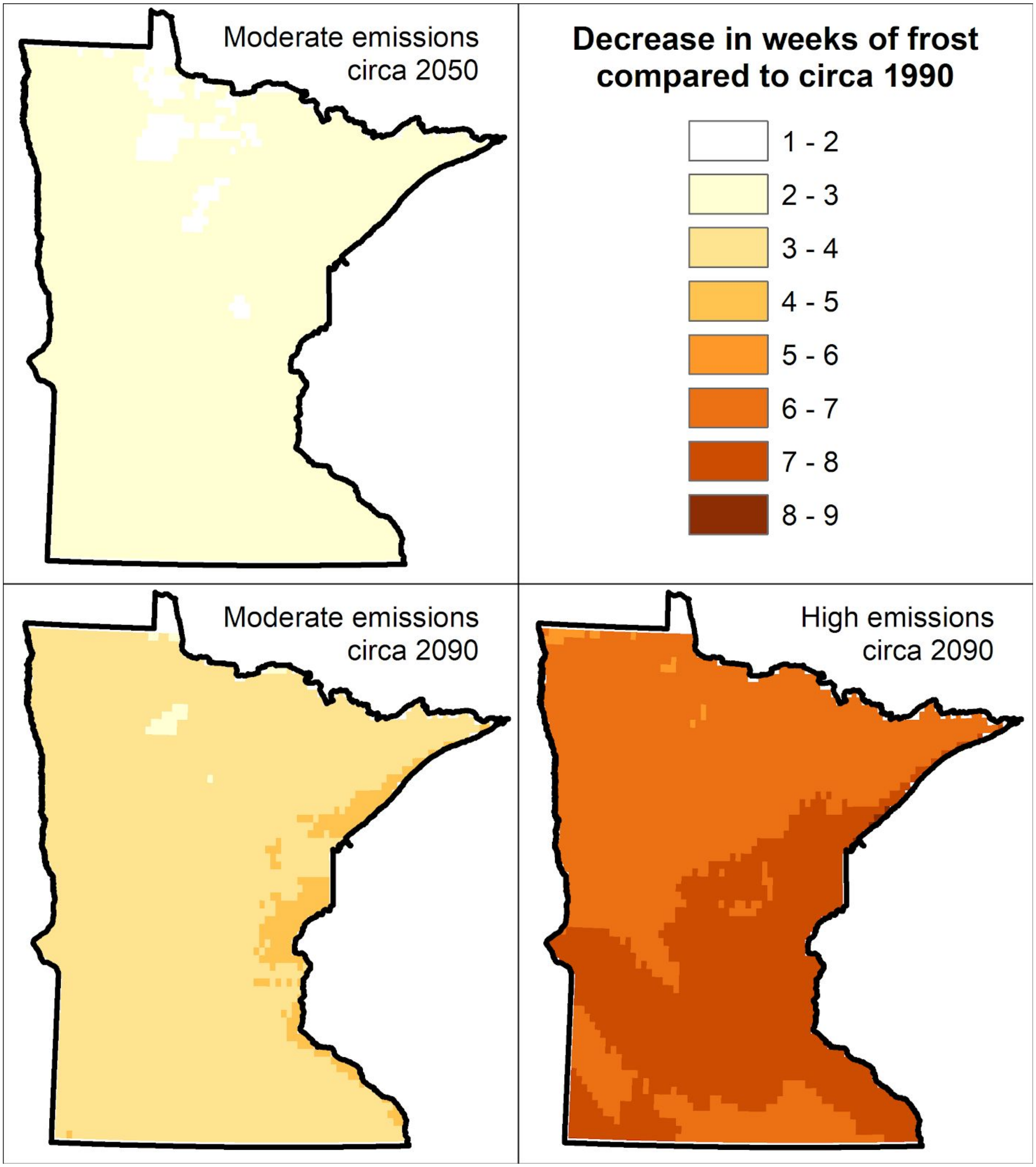

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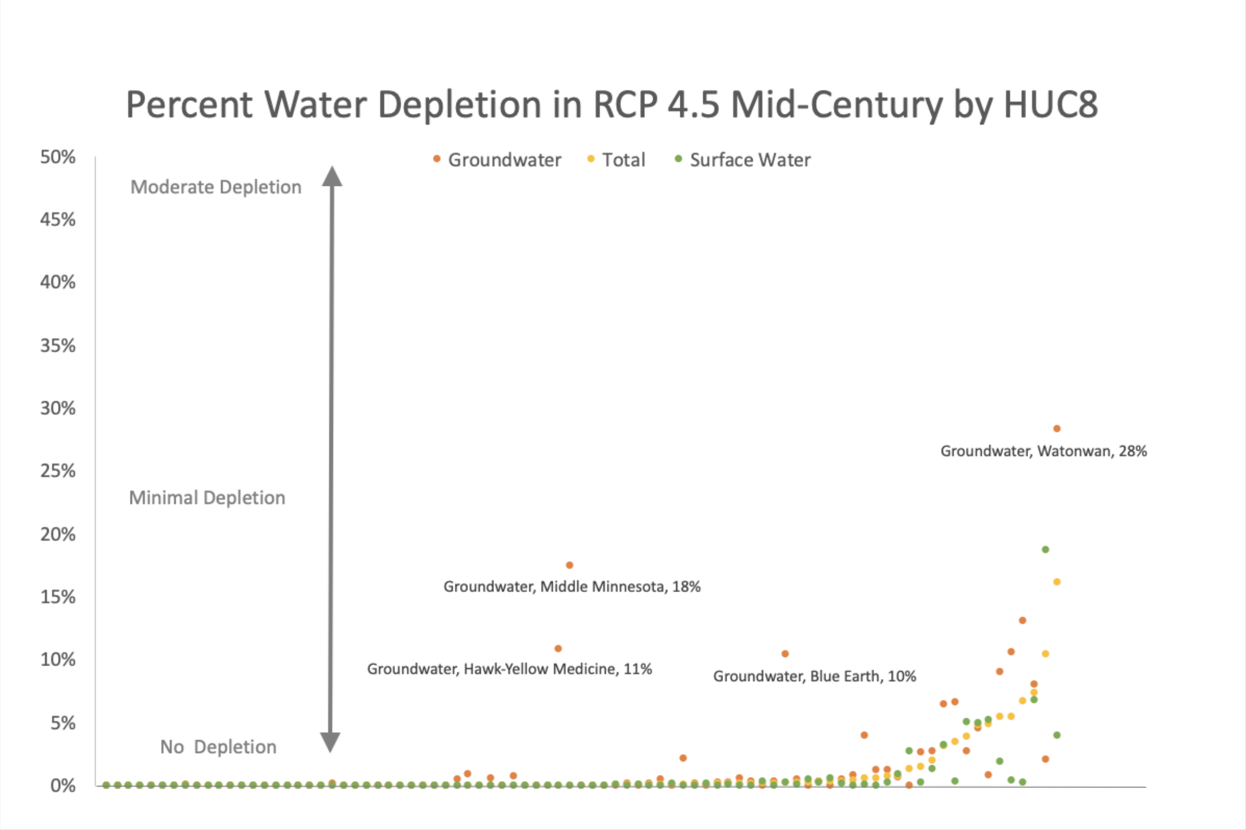

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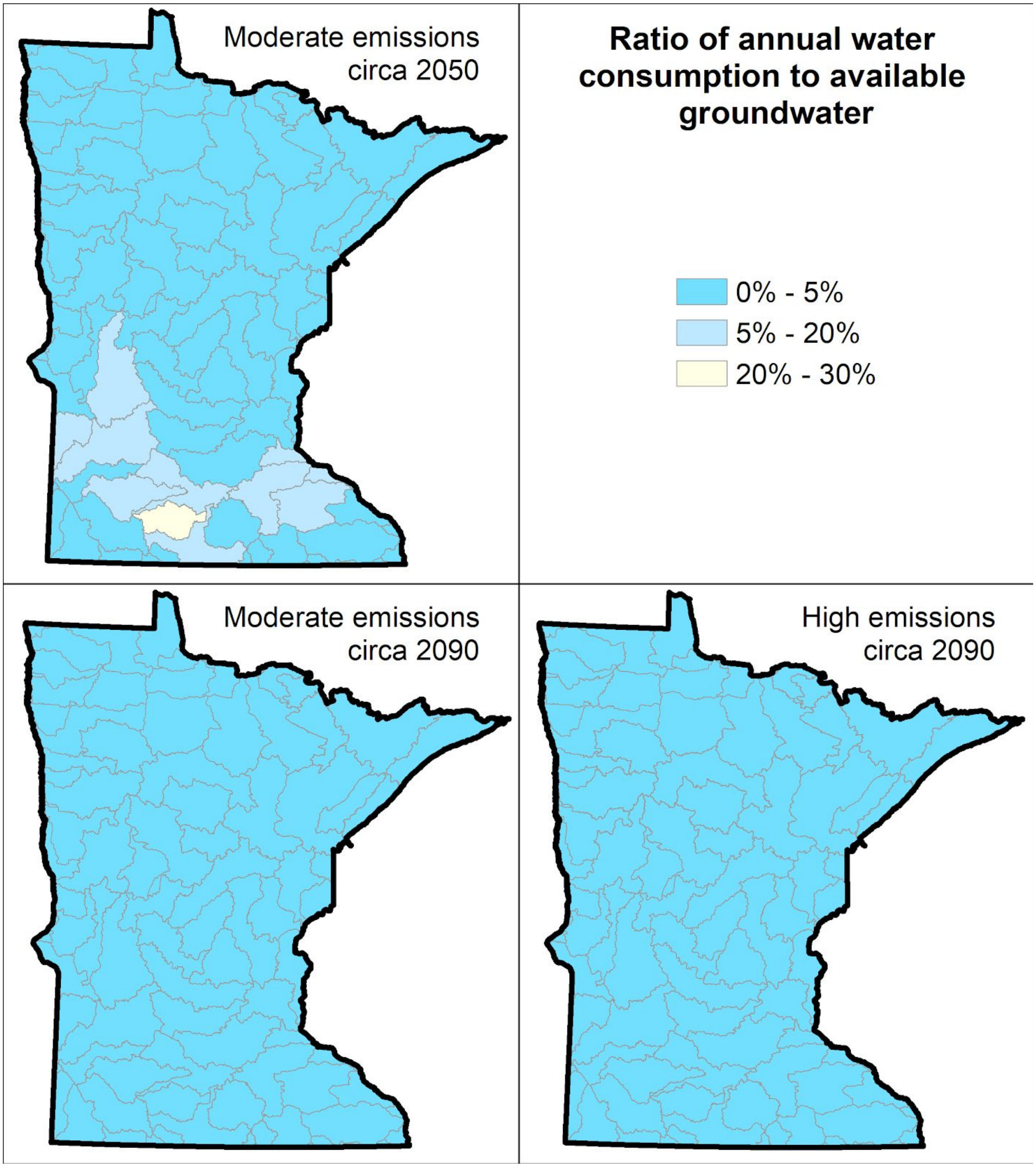

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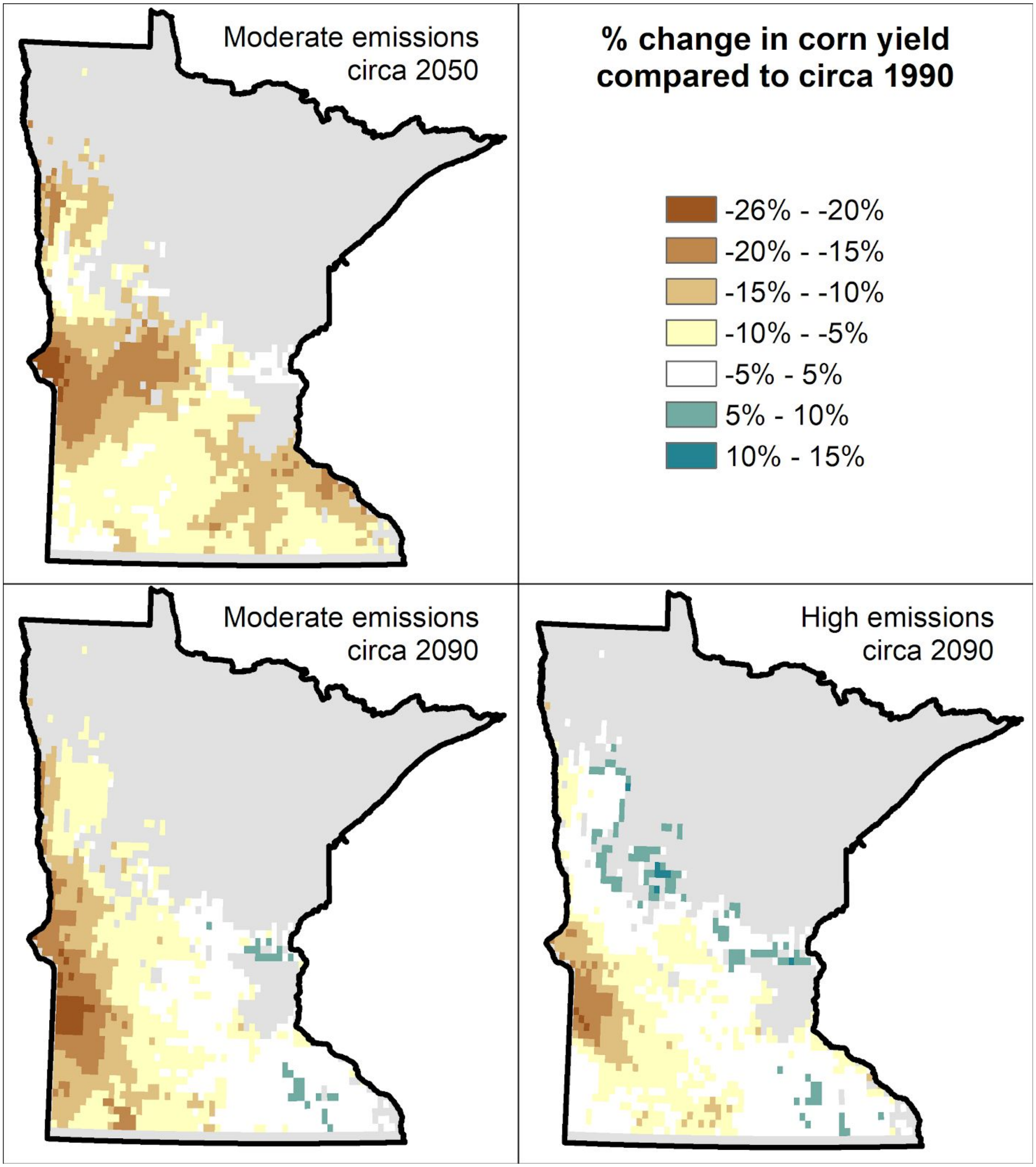

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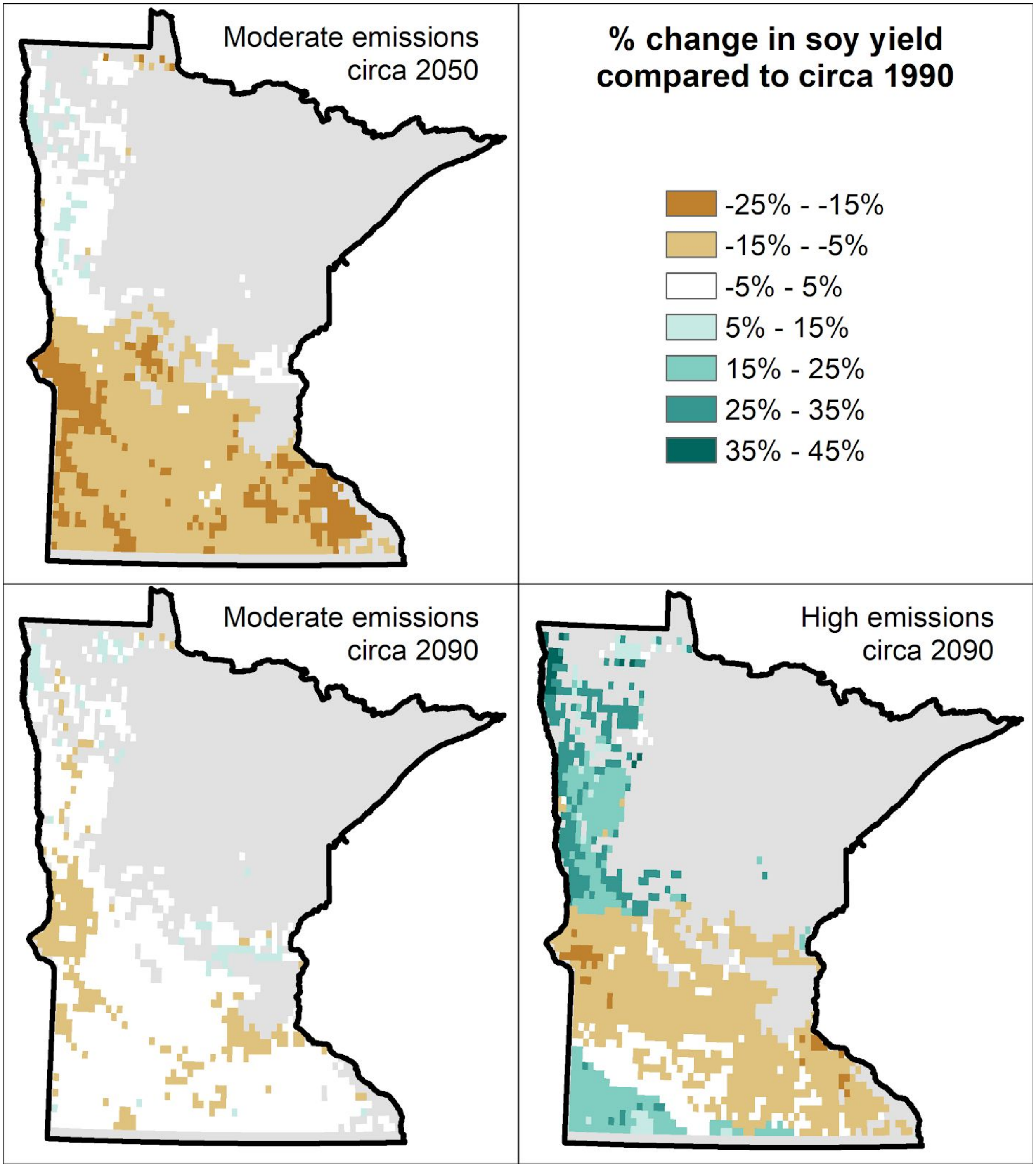

Figure 11. Percent change in soy yield.

Conclusions

From an annual average perspective, Minnesota is projected to be warmer with a consistent or greater quantity of precipitation relative to circa 1990. By dynamically downscaling global projections, we find that precipitation timing and intensity changes are likely. Although the annual quantity of precipitation will be similar or greater, we project similar or fewer days of precipitation and longer maximum dry spells. This results in more intense events that stress infrastructure and crop production. Corn yield declined in almost all regions and climate change scenarios, sometimes by as much as 25%. Warming trends will shorten winters, affecting winter recreation activities. In the summer, the state is projected to experience far more days with highs greater than or equal to 95°F.

With regards to water depletion, we did not find evidence for depletion annually. We found one watershed that had water consumption equivalent to 28% of its available groundwater in the mid-century period. This was the highest of any of the watersheds or scenarios analyzed, but is not extreme. Communities, especially those with elevated annual groundwater depletion, may have greater depletion on a short-term base and should consider surface water sources when expanding withdrawals. Our annual analysis is unable to detect short term depletion that could occur in response to longer dry spells under climate change. Our data products should be used in conjunction with models that include local geology to capture the influence of short term events on local features.

In an effort to provide tools for local communities to plan for climate change, we will make available the underlying data for this analysis after it has gone through the peer review process. Future updates can be found at https://z.umn.edu/climate-change-data.