Challenges to Ecosystem Management and Engineering Design in a Rapidly Changing Midwest Environment

ND-Energy Luncheon Seminar
3/28/2024

Alan F. Hamlet

Overview of the Talk

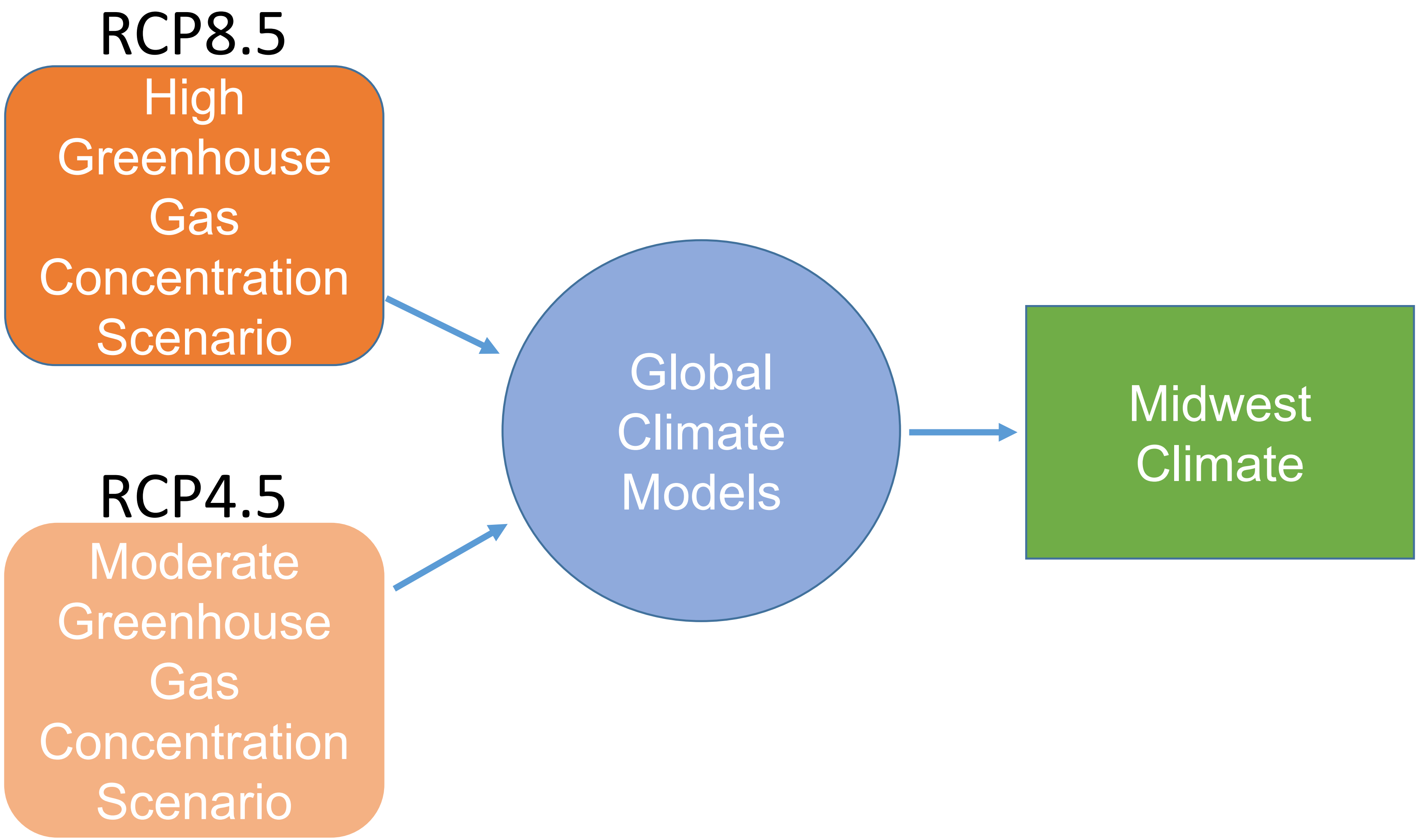
- *Brief Overview of Midwest Climate Change*
  - Projections of future temperature and precipitation
  - Hydrologic impacts in Midwest watersheds

- *Ecosystems*
  - Impacts to small northern lakes
  - Nutrient loss in agricultural watersheds

- *Water Resources*
  - ND Hydropower Plant Design Study
  - Hydrologic Design Standards in a Non-Stationary Climate
  - Coping with Emerging Ultra Extremes

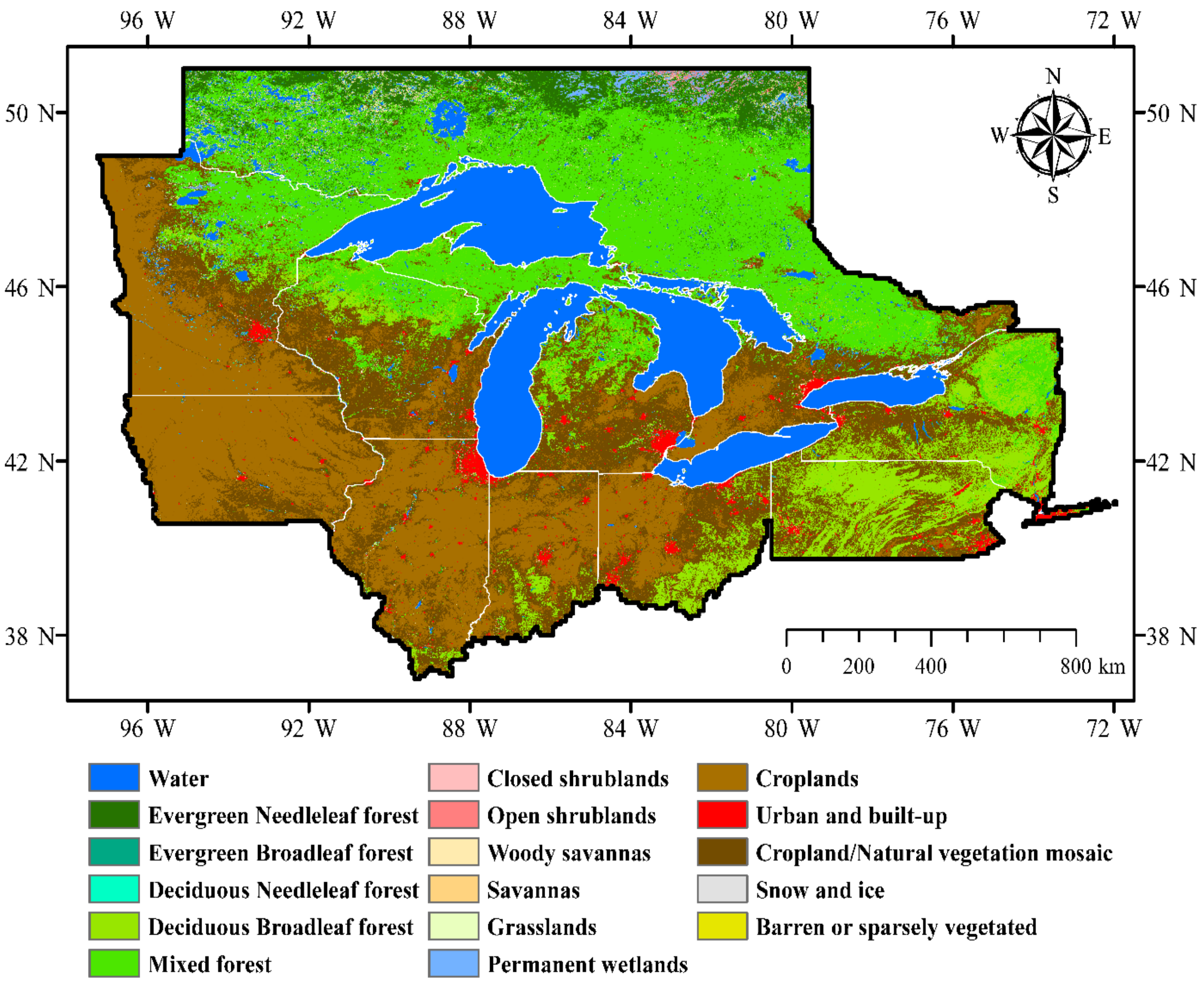
Climate Change Projections for the Midwest

Using Global Climate Models to Simulate the Future

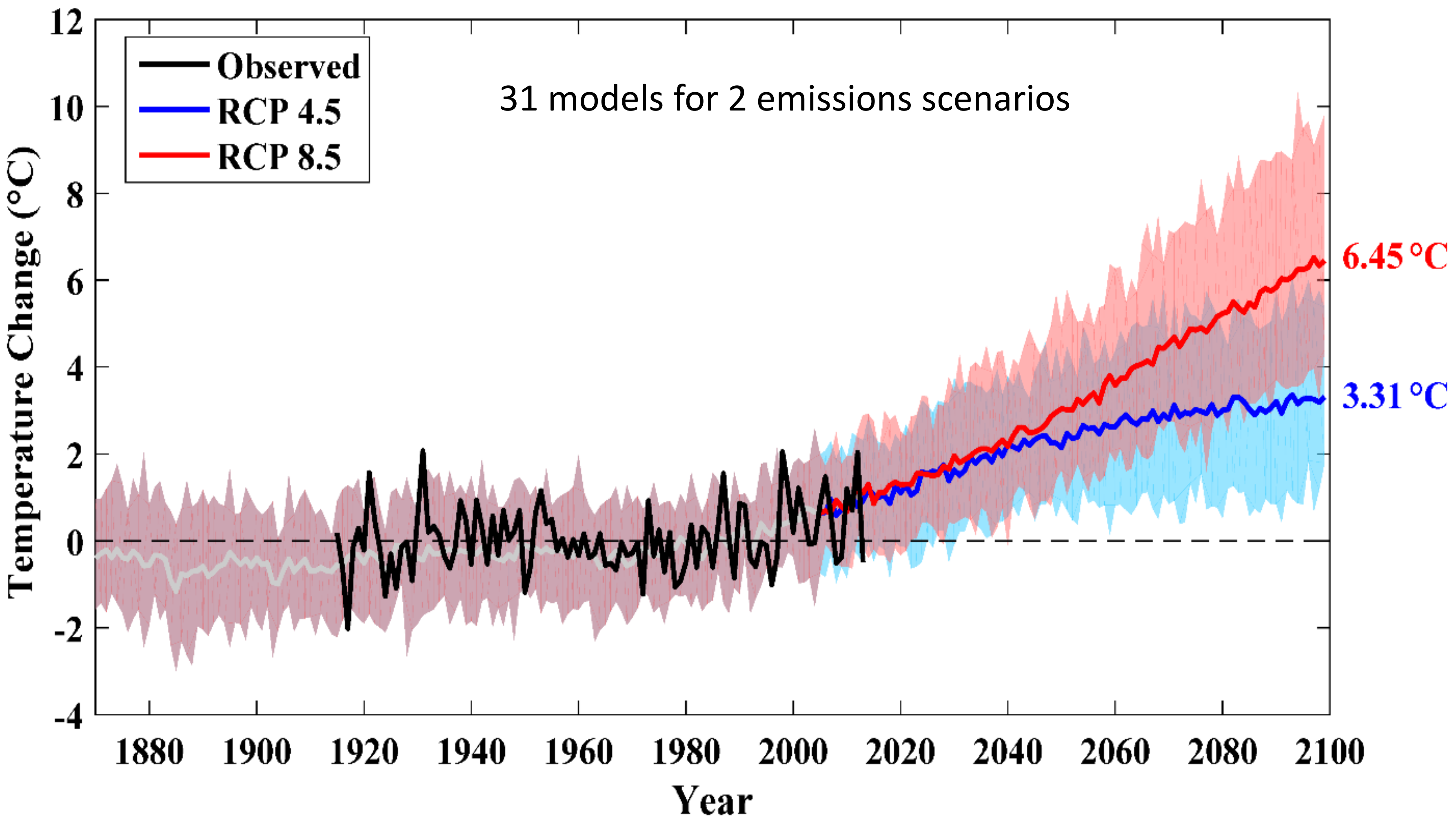


Midwest and Great Lakes Study Domain

Resolution
5x7 km

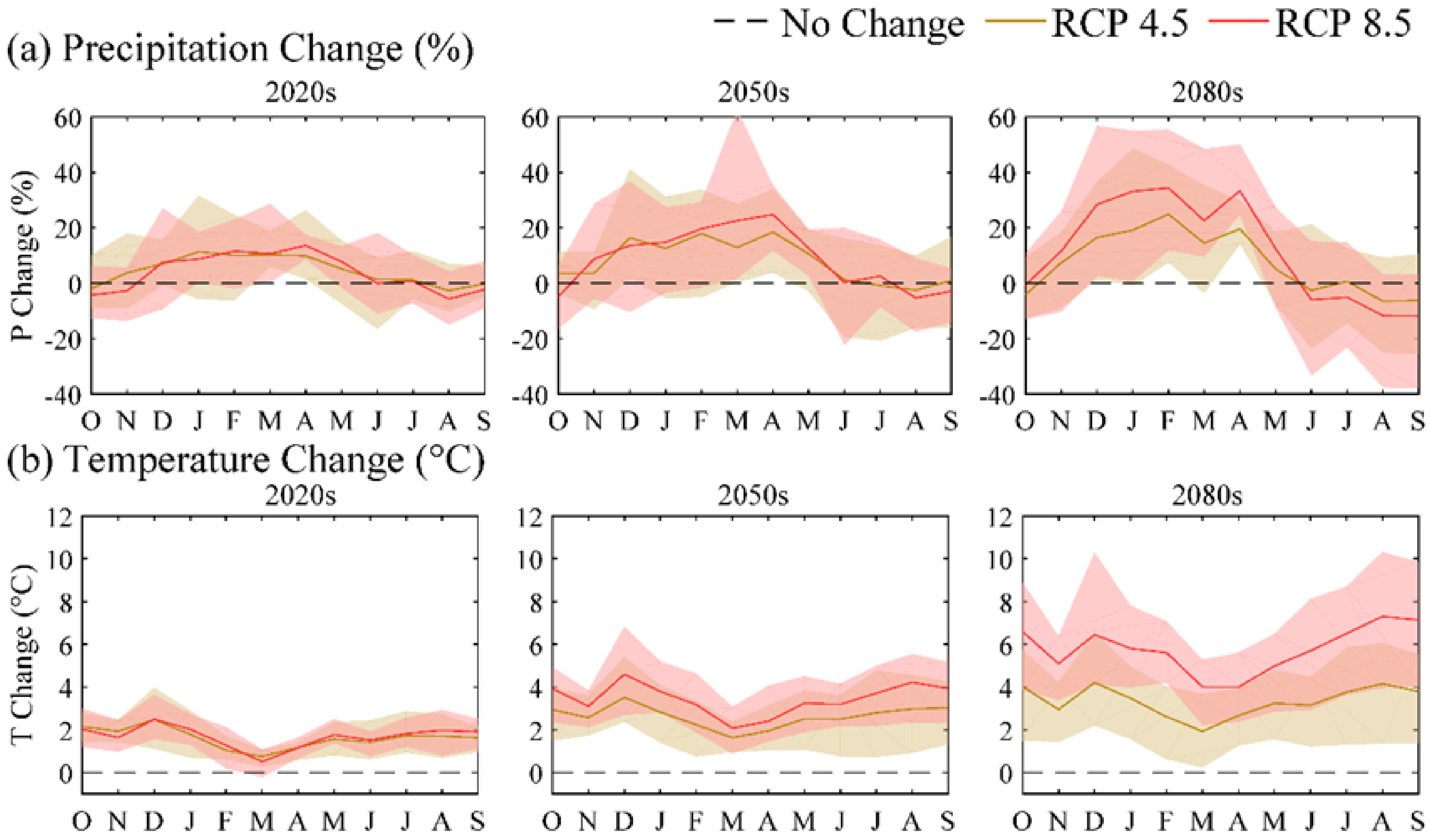


Projections of Future Climate Over the Midwest



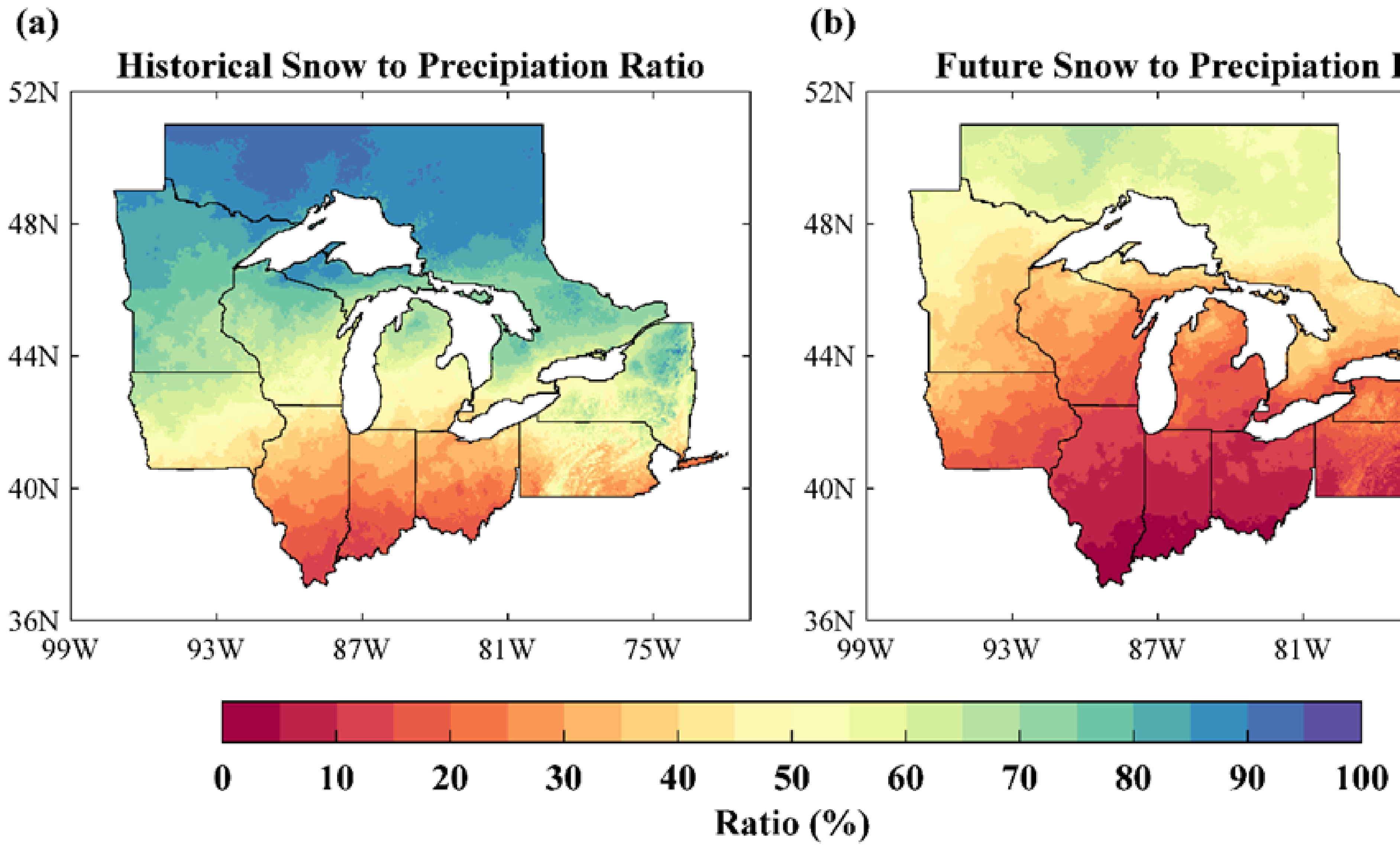
Byun, K. and A.F. Hamlet, 2018: Projected Changes in Future Climate over the Midwest and Great Lakes Region Using Downscaled CMIP5 Ensembles, International Journal of Climatology, DOI: 10.1002/joc.5388

Projected Changes in P and T for the Midwest



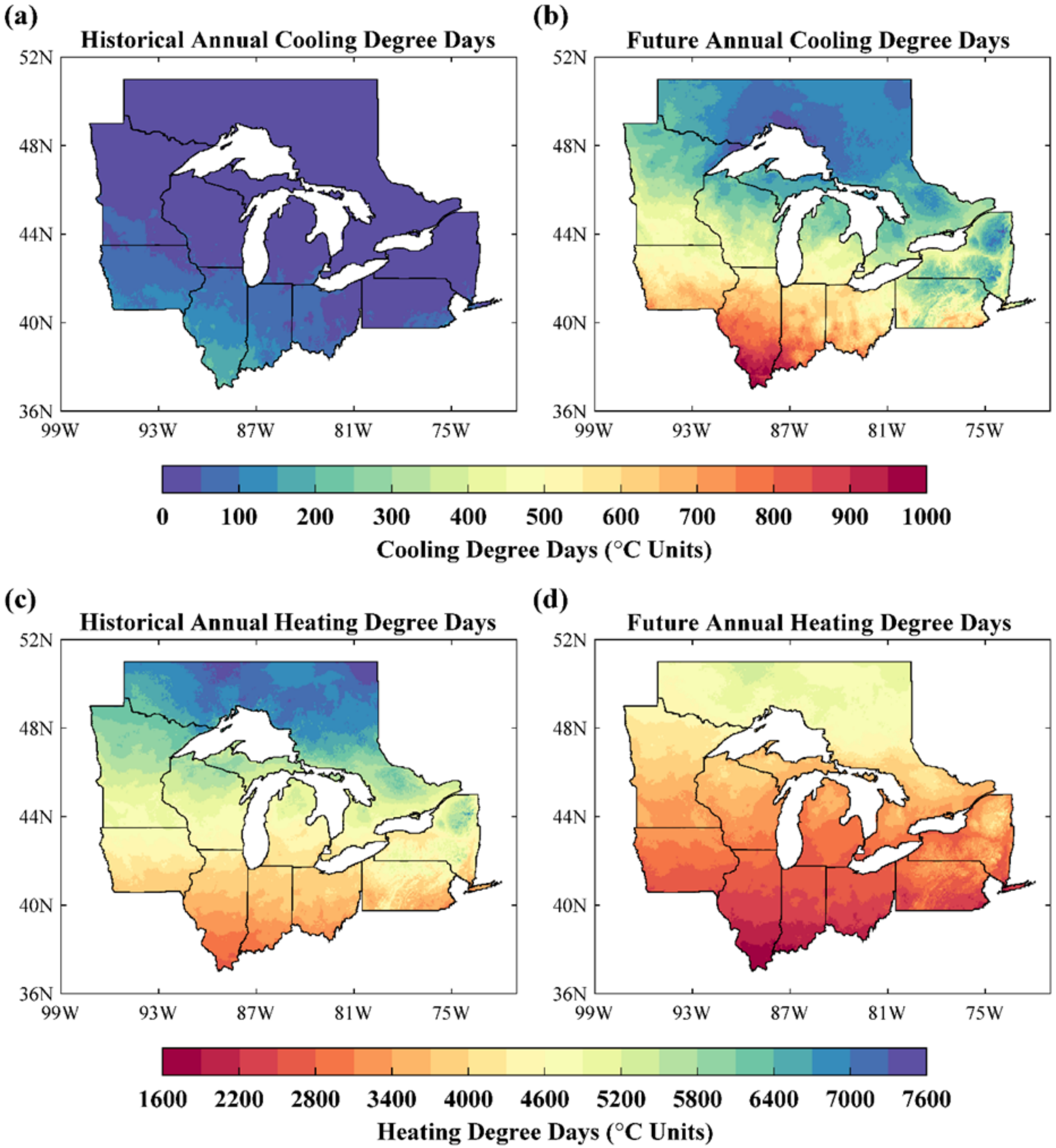
Byun, K. and A.F. Hamlet, 2018: Projected Changes in Future Climate over the Midwest and Great Lakes Region Using Downscaled CMIP5 Ensembles, International Journal of Climatology, DOI: 10.1002/joc.5388

Fraction of Nov-March Precipitation Falling as Snow



Projected Changes in Cooling and Heating Degree Days

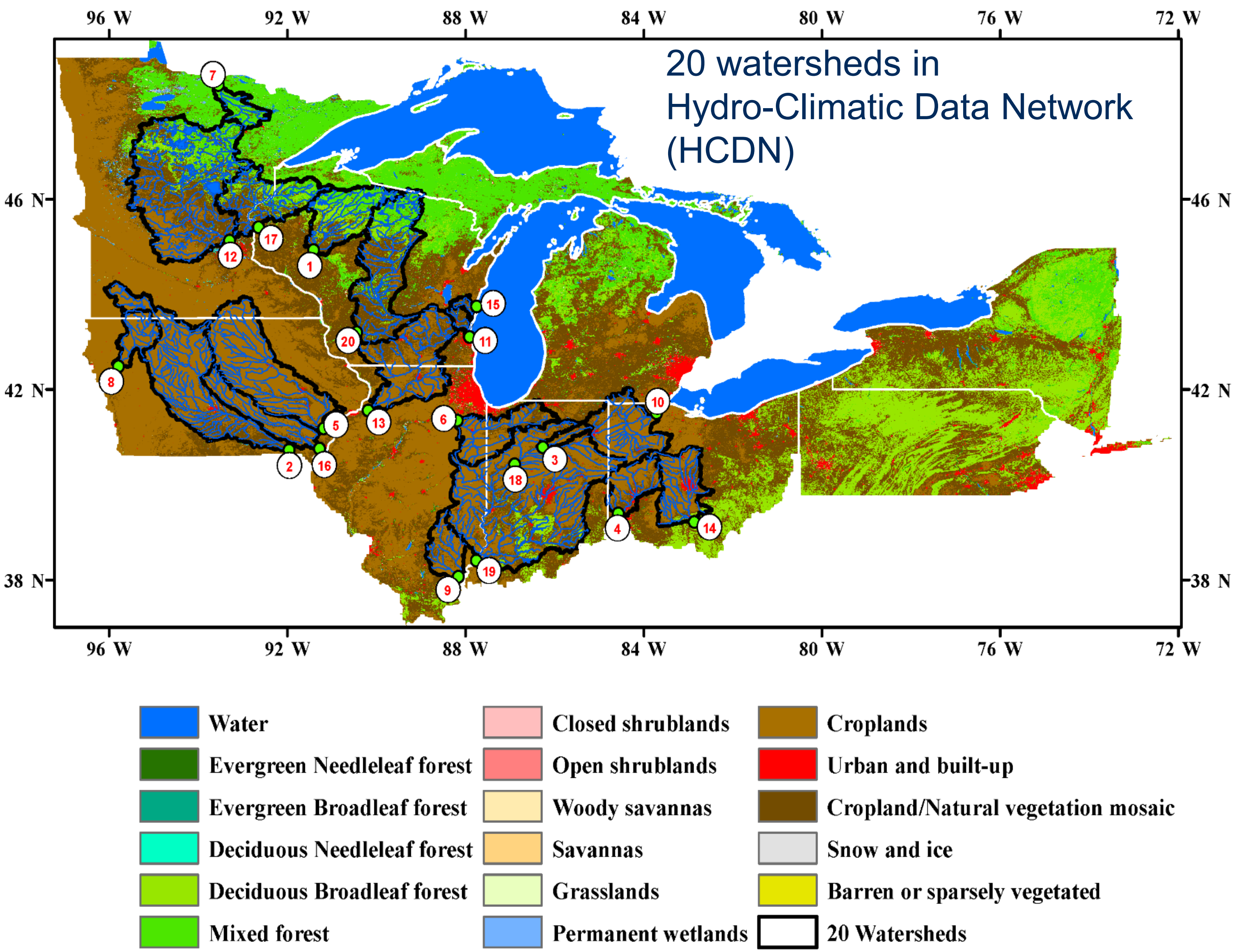
RCP8.5 2080s



Effects of Climate Change on Seasonal Flow and Hydrologic Extremes in Midwest Rivers

Byun, K., C.-M. Chiu, A.F. Hamlet, 2018: Effects of 21st Century Climate Change on Seasonal Flow Regimes and Hydrologic Extremes over the Midwest and Great Lakes Region of the U.S., Science of the Total Environment, 650(1):1261-1277, DOI:10.1016/j.scitotenv.2018.09.063.

Domain of Case Study



Changes in Monthly Streamflow

Historical Run (HR) Streamflow — Ensemble Mean of Climate Change Run (CCR) Streamflow

Monthly Streamflow (mm)

- Change in Seasonality

  - Increase in peak seasonal flow in most watersheds

  - Some watershed shows decreasing or about the same peak, but with critical shift of timing

  - Implications of seasonal changes:

  e.g. Increasing flood risk
  Disturbance on ecosystems

Ecosystem Impacts

Quantifying Climate Change Impacts to Small Lakes and Wetlands in the Midwest

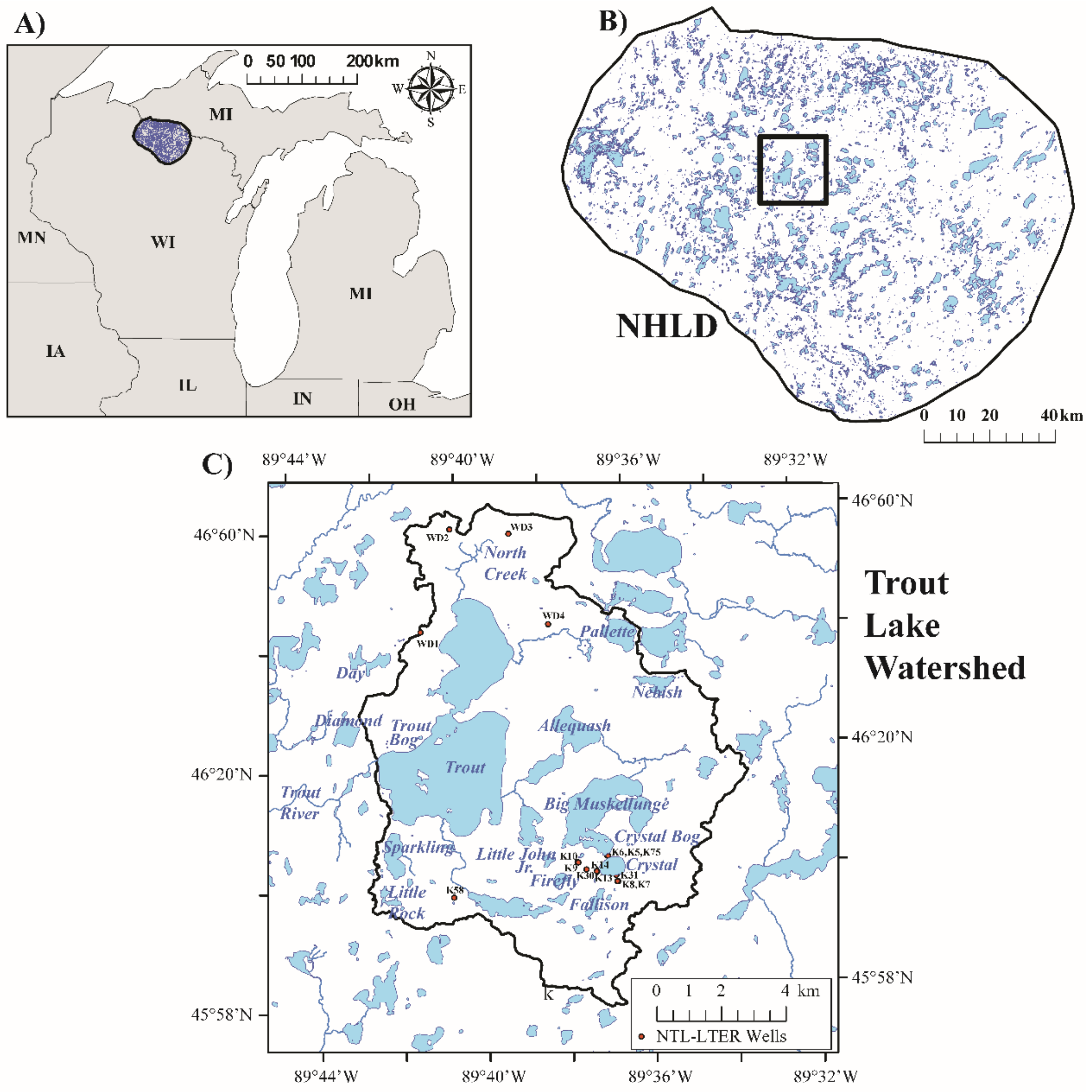
Hanson, Z., J. Zwart, J. Vanderall, C. T. Solomon, A. F. Hamlet, S. Jones, D. Bolster, 2018: Integrated, Regional-Scale Hydrologic Modeling of Inland Lakes, Journal of the American Water Resources Association, DOI: 10.1111/1752-1688.12688.

Zwart, J. A., Z. J. Hanson, J. Vanderwall, D. Bolster, A. F. Hamlet, S. E. Jones, 2018: Spatially explicit, regional-scale simulation of lake carbon fluxes, Global Biogeochemical Cycles, DOI: 10.1002/2017GB005843

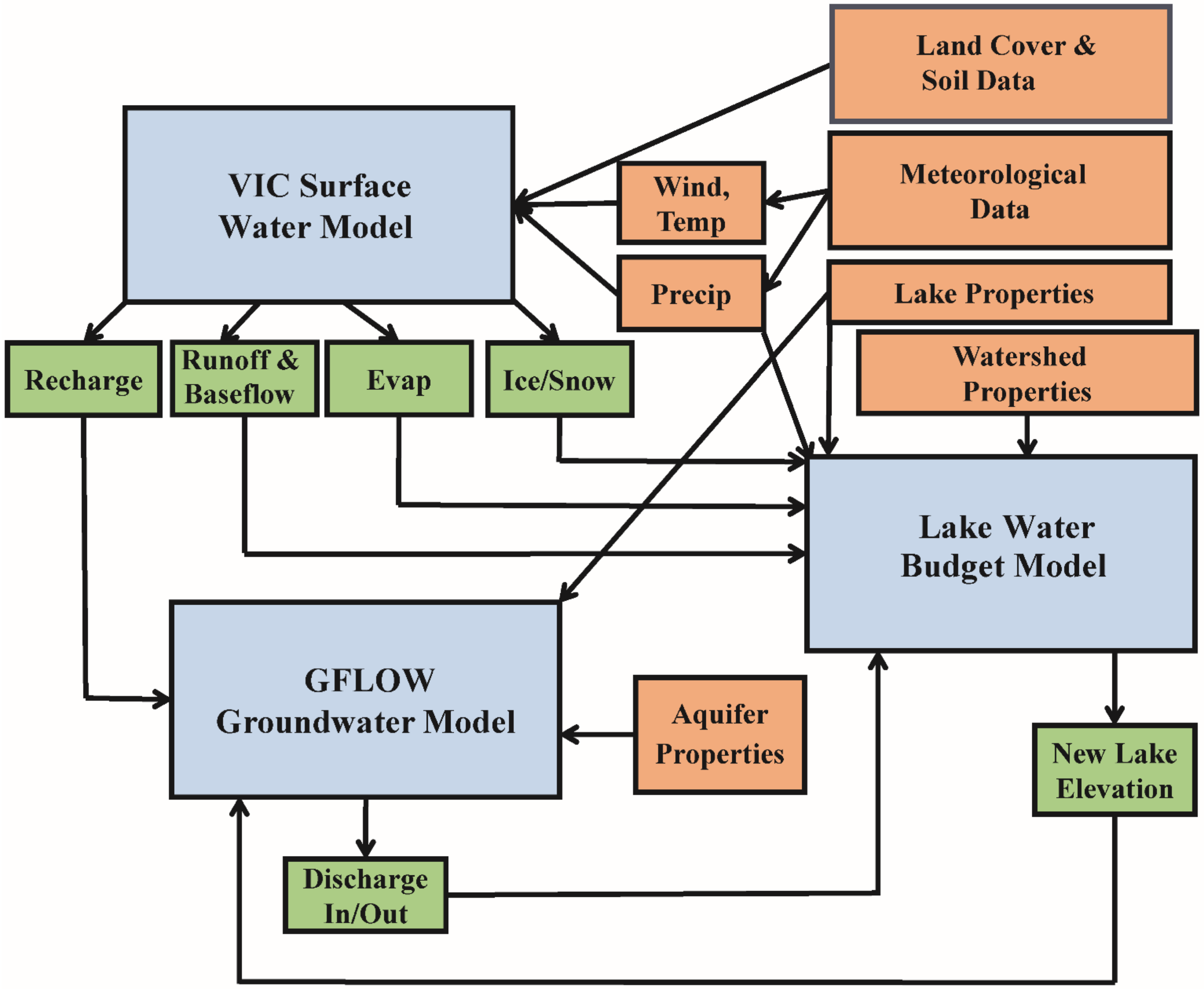
Zwart, J. A., Z. J. Hanson, J. S. Read. M. N. Fienan, A. F. Hamlet, D. Bolster, S. E. Jones, 2019: Cross-scale interactions dictate regional lake carbon flux and productivity response to future climate, Geophysical Research Letters, 46 (15): 8840-8851, https://doi.org/10.1029/2019GL083478

Regional-scale modeling of the NHLD

- Northern Highland Lake District
- Lake-rich landscape
  - 6000 km^2
  - 4000 lakes
- Decades of observations
  - SW and GW



Integrated SW/GW/Lake Modeling



Useful Hydrologic Metrics

- **Hydrologic Residence Time** (HRT)

$$HRT = \frac{Volume}{Inflows}$$

Volume [L^3]
Inflows [L^3/T]
HRT [T]

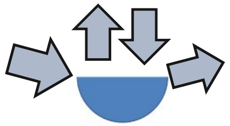
- **Fraction of Hydrologic Export as Evaporation** (FHEE)

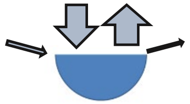
$$FHEE = \frac{\overline{E}}{\overline{E} + \overline{GW_{out}} + \overline{SW_{out}}}$$

E, GW_{out} , SW_{out} [L^3/T]
FHEE [*]

- Why are these helpful?
  - Hydrologic and biogeochemical processing time (HRT)
  - Lake classification across spectrum (FHEE; drainage, seepage)

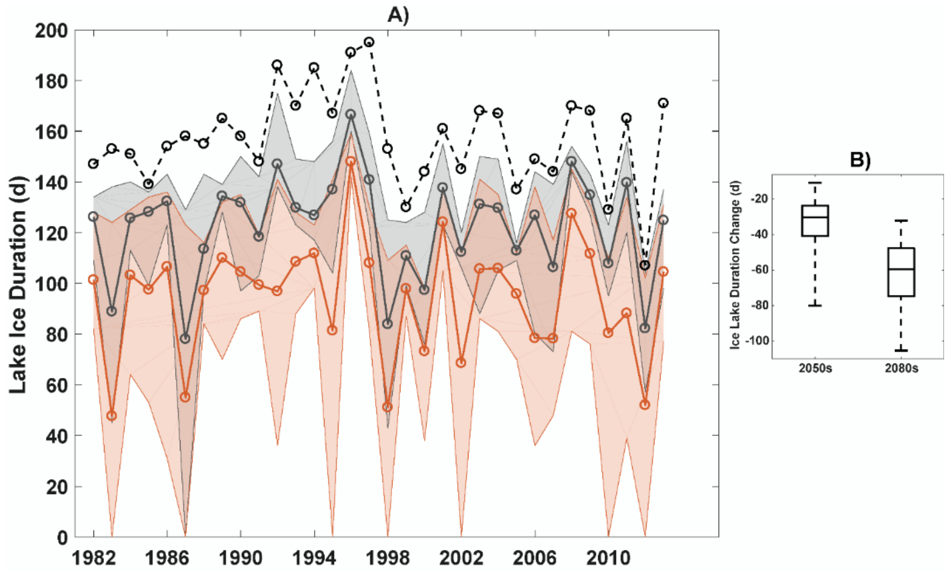
Low FHEE

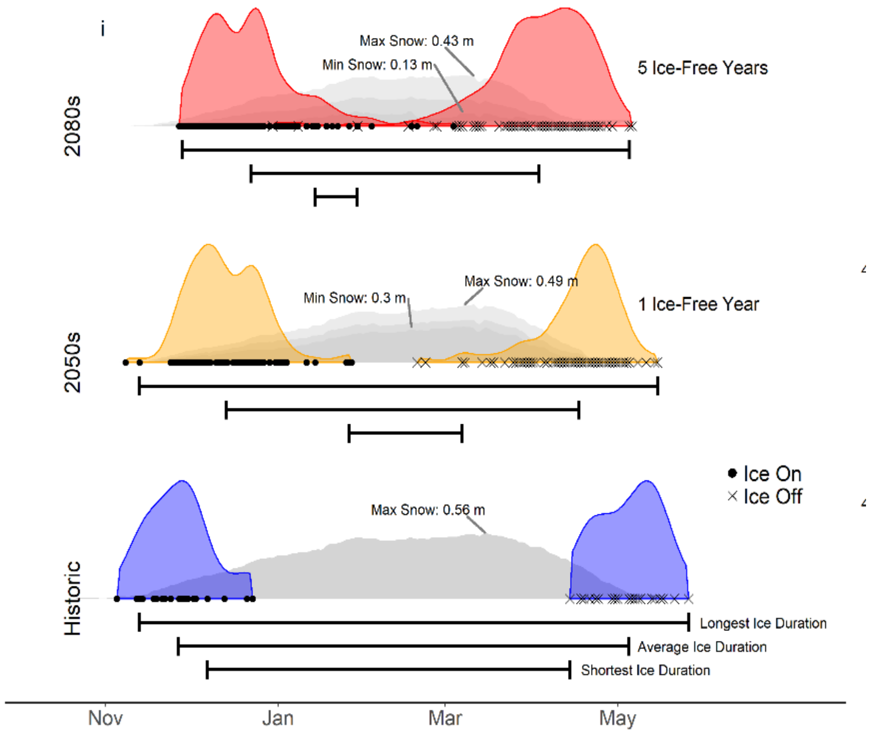




High FHEE

Lake Ice Response



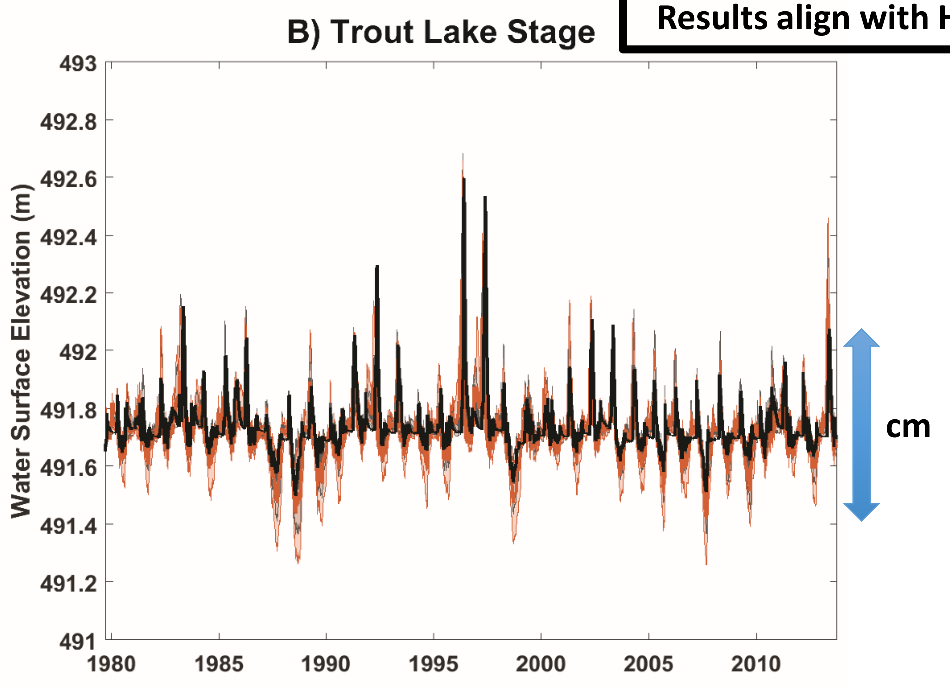


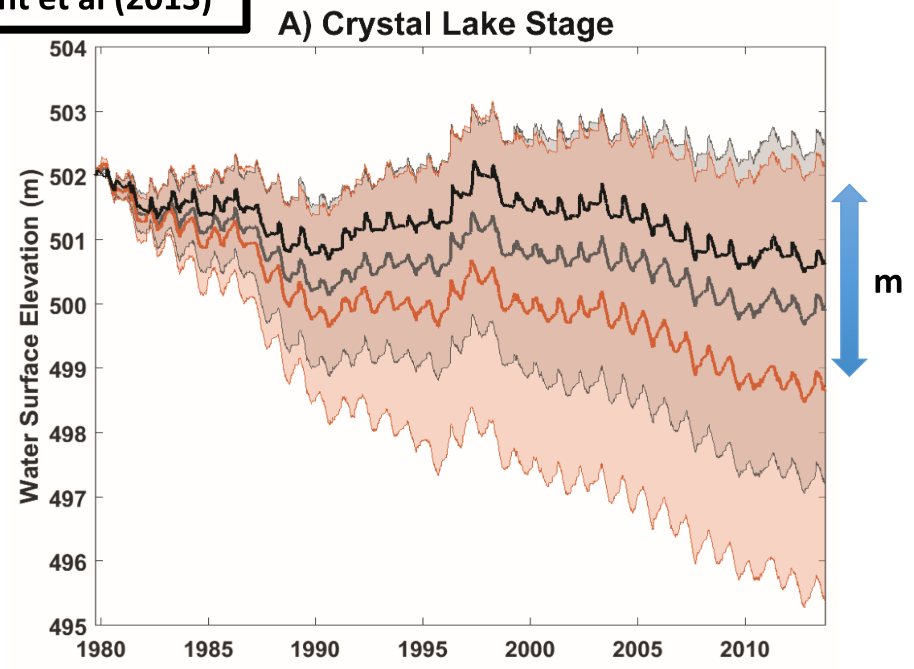
Average Ice duration reduction:

35 days (2050s)
63 days (2080s)

Changes in Lake Levels Depend on Lake Hydrologic Characteristics

Results align with Hunt et al (2013)



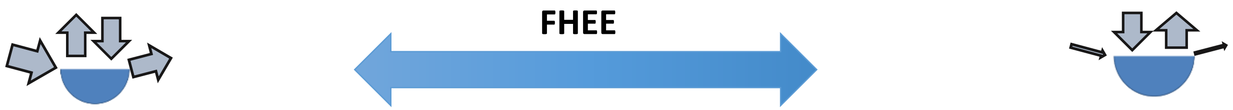


Trout Average Minimum Lake Level Changes:

0.02 m (2050s)
0.08 m (2080s)

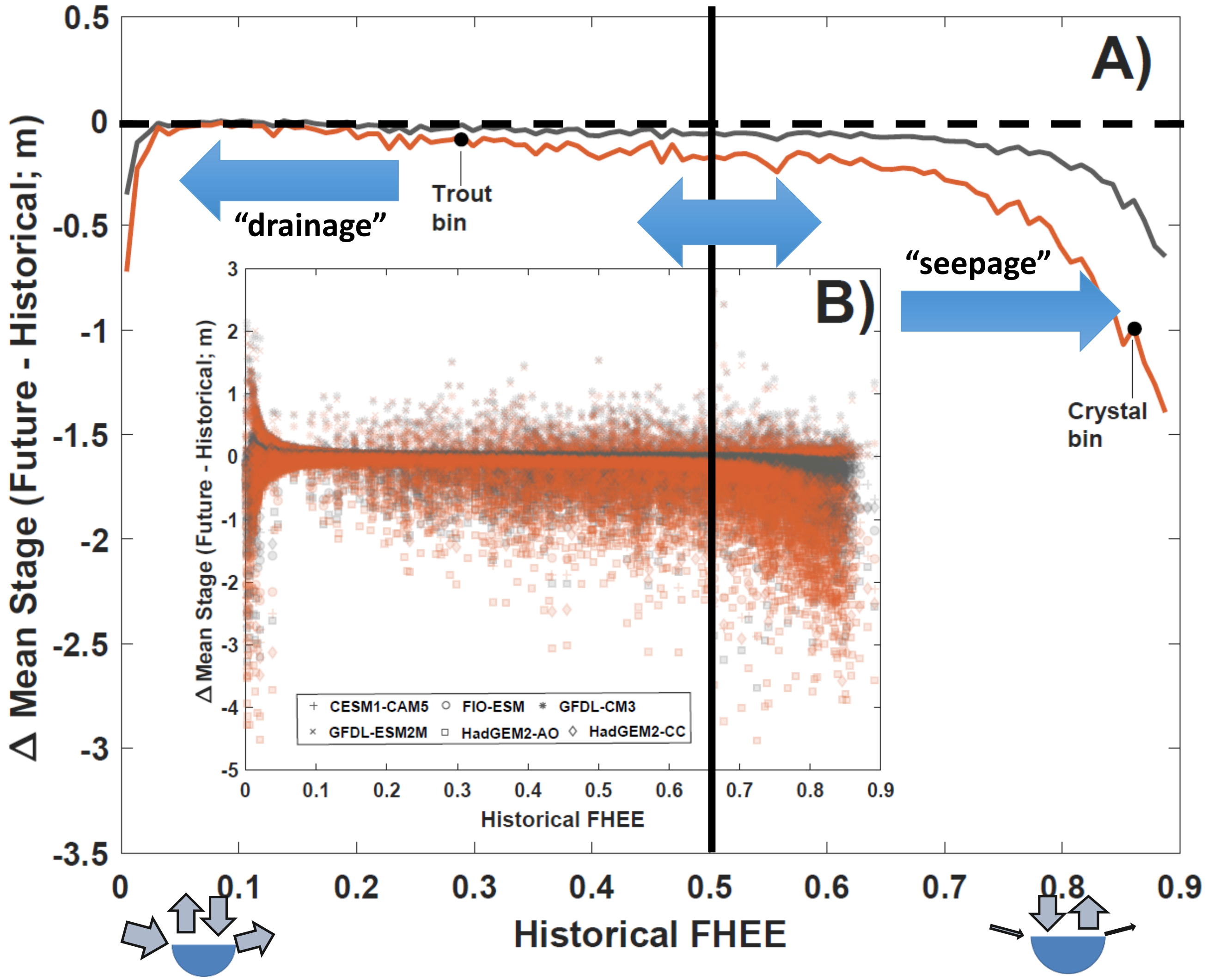
Crystal Average Minimum Lake Level Changes:

0.80 m (2050s)
2.04 m (2080s)

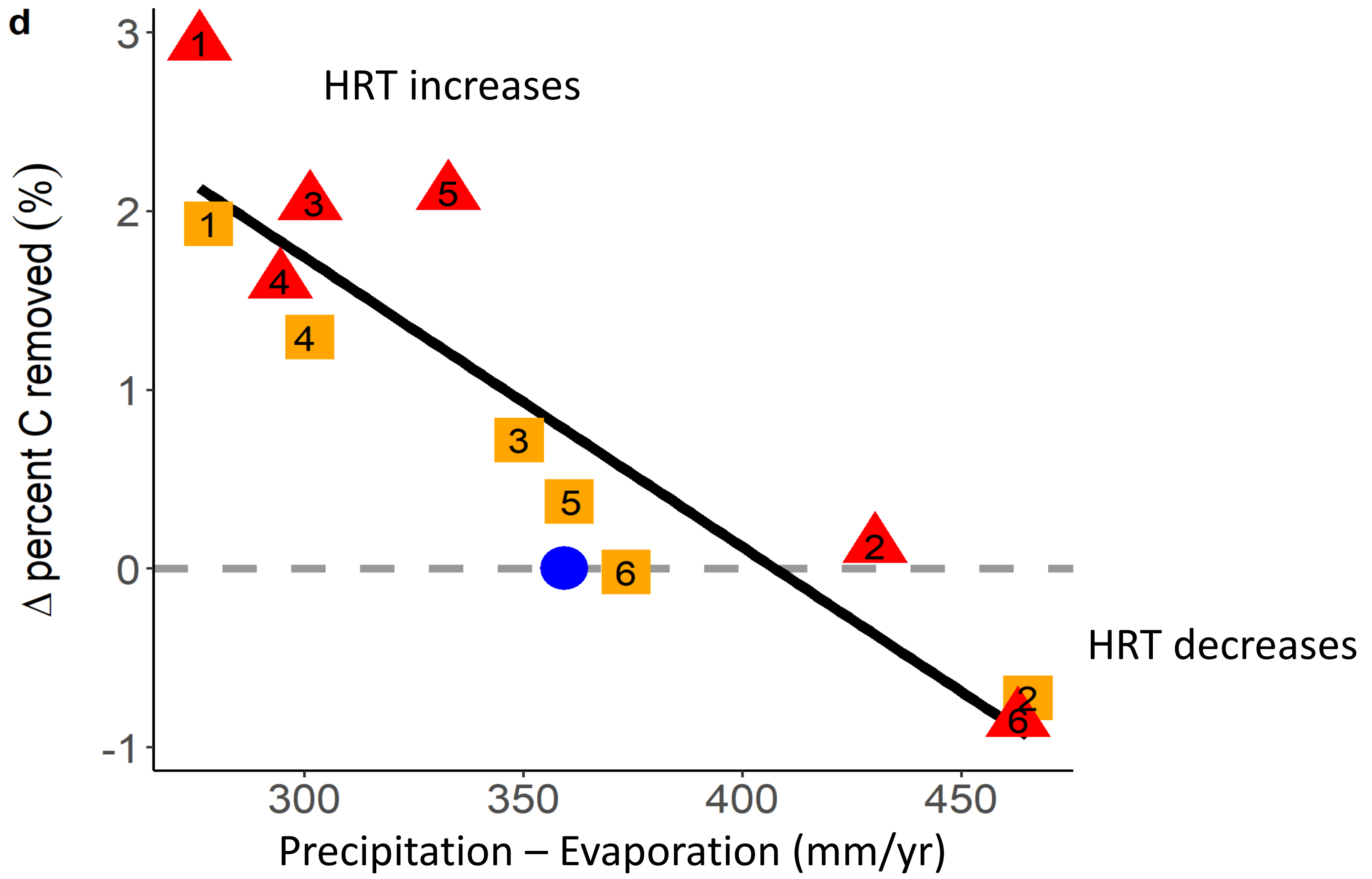


How do these hydrologic changes effect the NHLD lake population?

In response to CC, **lake levels** remain relatively constant in drainage lakes, but decrease in seepage lakes.

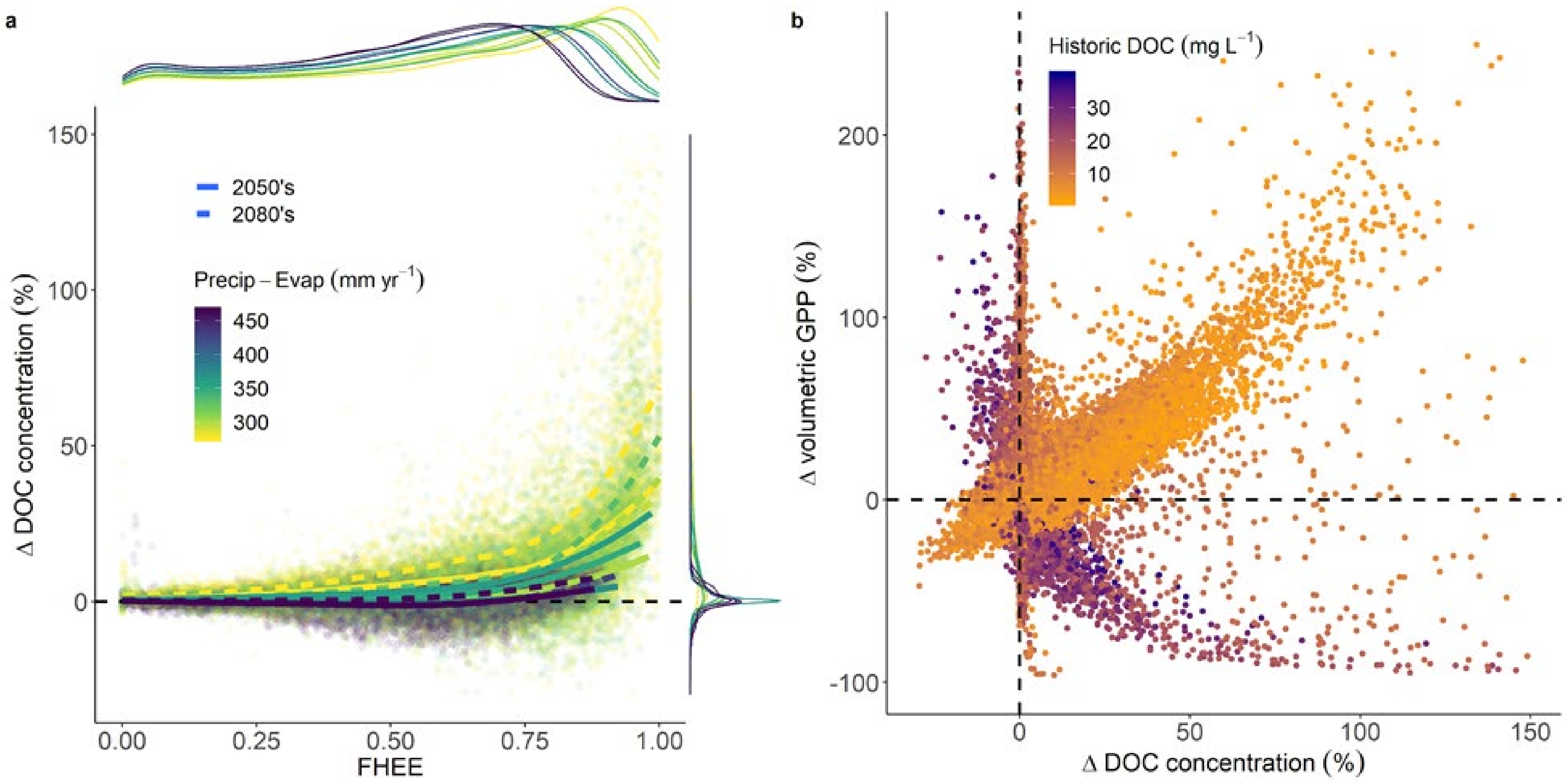


Lakes Remove About the Same or Slightly More Carbon (as %) for Most Scenarios



Zwart, J. A., Z. J. Hanson, J. S. Read. M. N. Fienan, A. F. Hamlet, D. Bolster, S. E. Jones, 2019: Cross-scale interactions dictate regional lake carbon flux and productivity response to future climate, Geophysical Research Letters, 46 (15): 8840-8851, https://doi.org/10.1029/2019GL083478

Effects of Climate Change on Changing Dissolved Organic Carbon Concentration and Gross Primary Production in NHLD Lakes



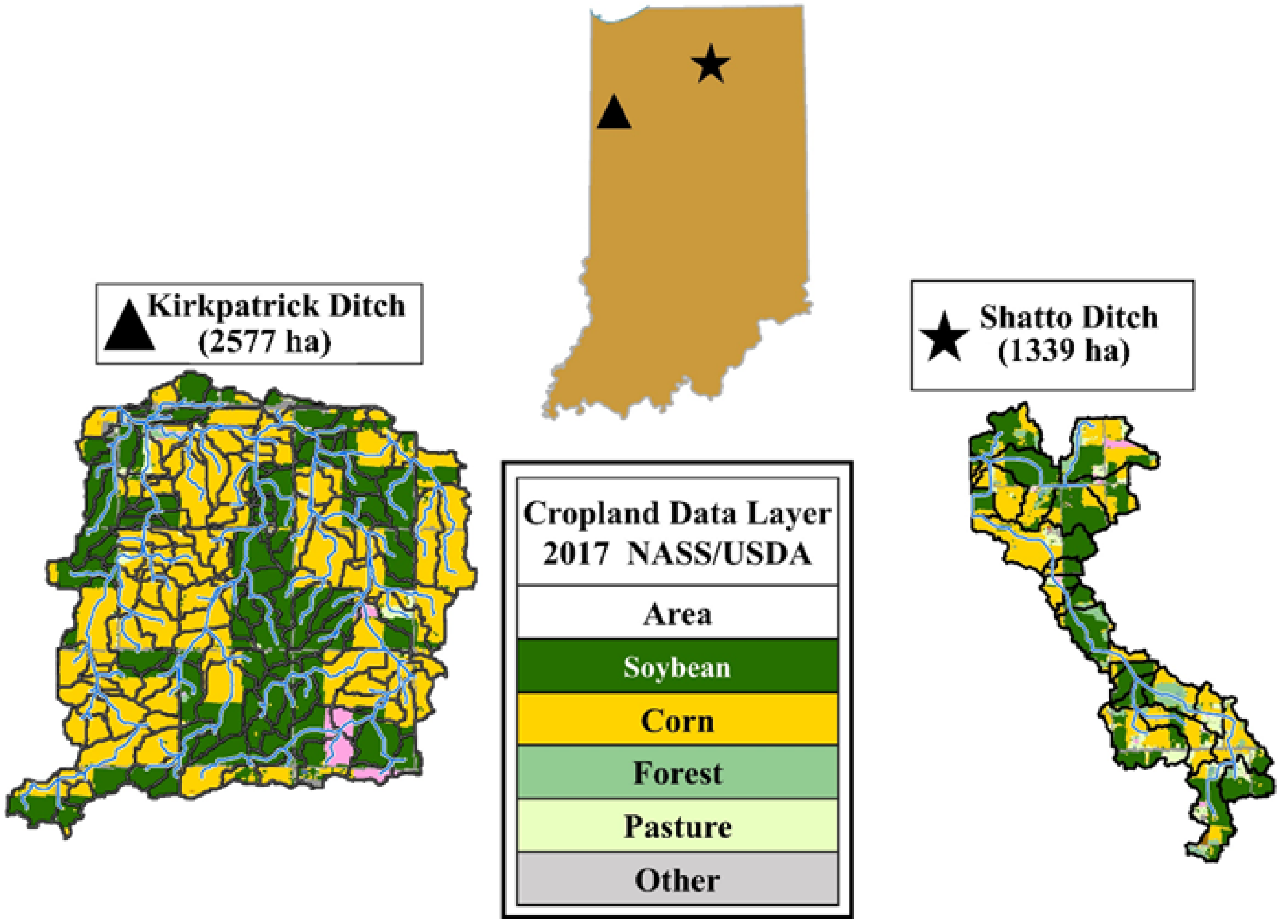
Zwart, J. A., Z. J. Hanson, J. S. Read. M. N. Fienan, A. F. Hamlet, D. Bolster, S. E. Jones, 2019: Cross-scale interactions dictate regional lake carbon flux and productivity response to future climate, Geophysical Research Letters, 46 (15): 8840-8851, https://doi.org/10.1029/2019GL083478

Combined Effects of Climate Change and Winter Cover Crops on Nutrient Losses in Agricultural Watersheds

Hamlet, A. F., N. Ehsani, J. L. Tank, Z. Silver, U. H. Mahl, K. Byun, S. L. Speir, M. T. Trentman, T. V. Royer, 2024: Effects of climate and winter cover crops on nutrient loss in agricultural watersheds in the midwestern U.S., *Climatic Change*, 177(9), DOI: 10.1007/s10584-023-03656-4.

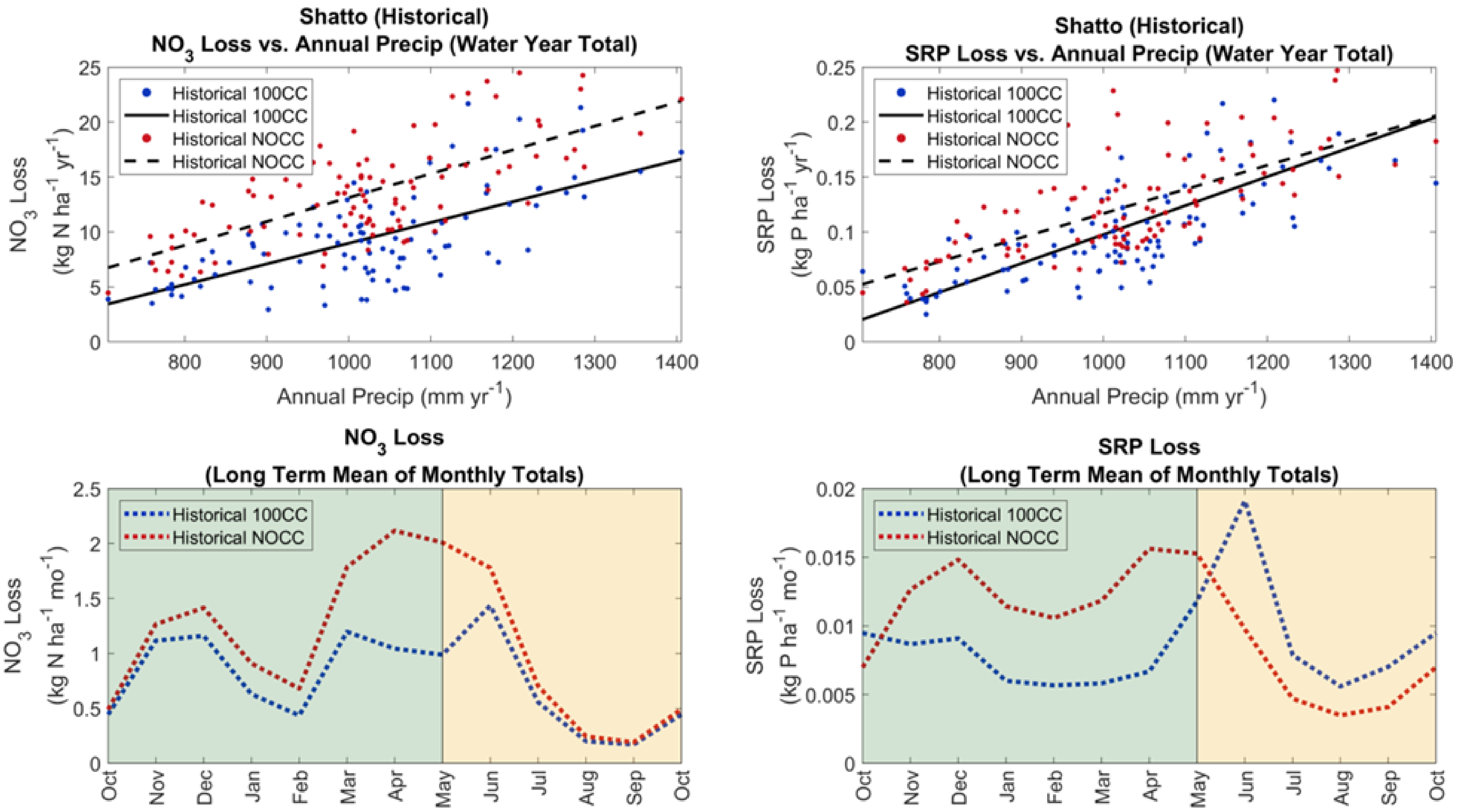
Gulf of Mexico Dead Zone

SWAT Simulations for Two Representative Agricultural Watersheds

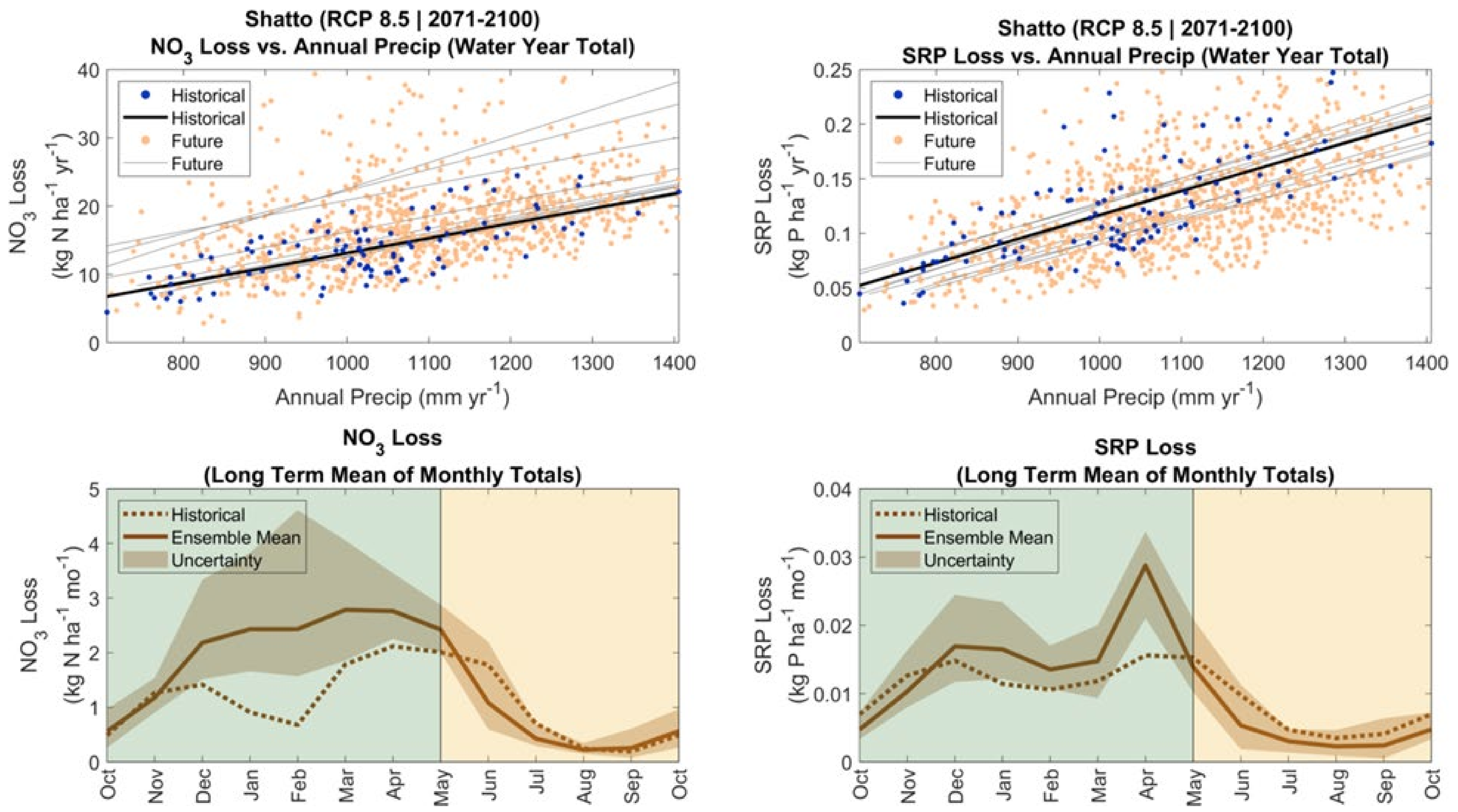


Cereal Rye Winter Cover Crop in April (at Maturity)

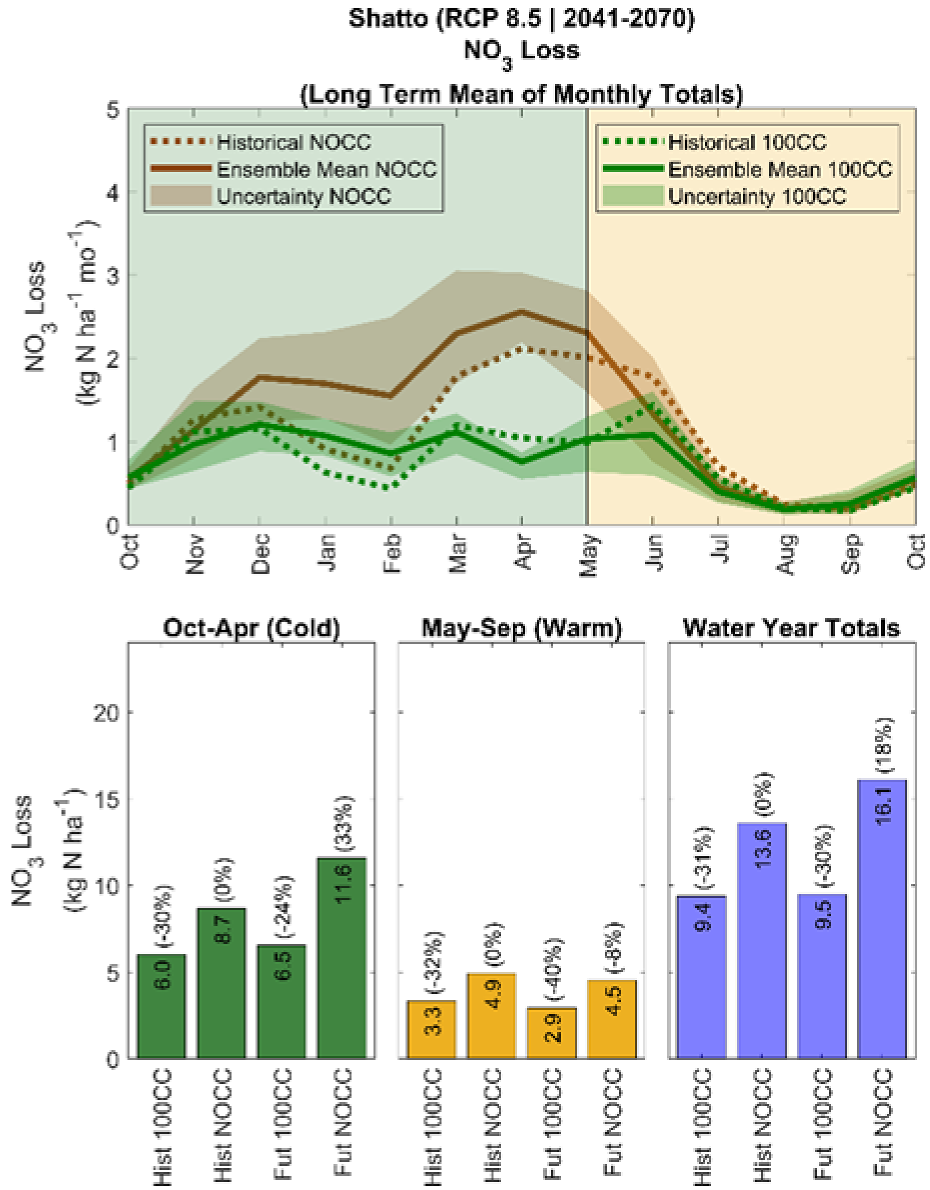
Effects of Cover Crops Alone

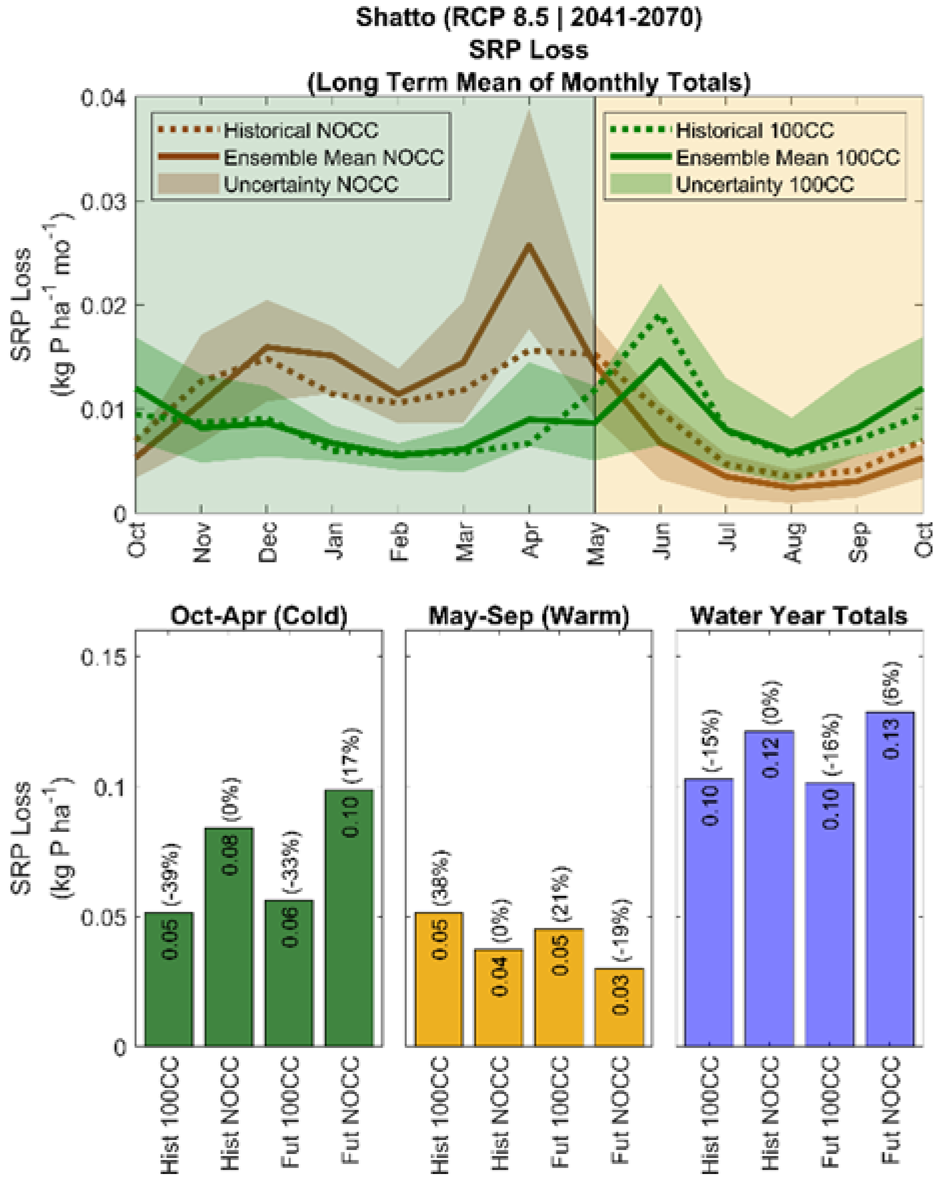


Effects of Climate Change Alone



Combined Effects of Winter Cover Crops and Climate Change RCP8.5 2050



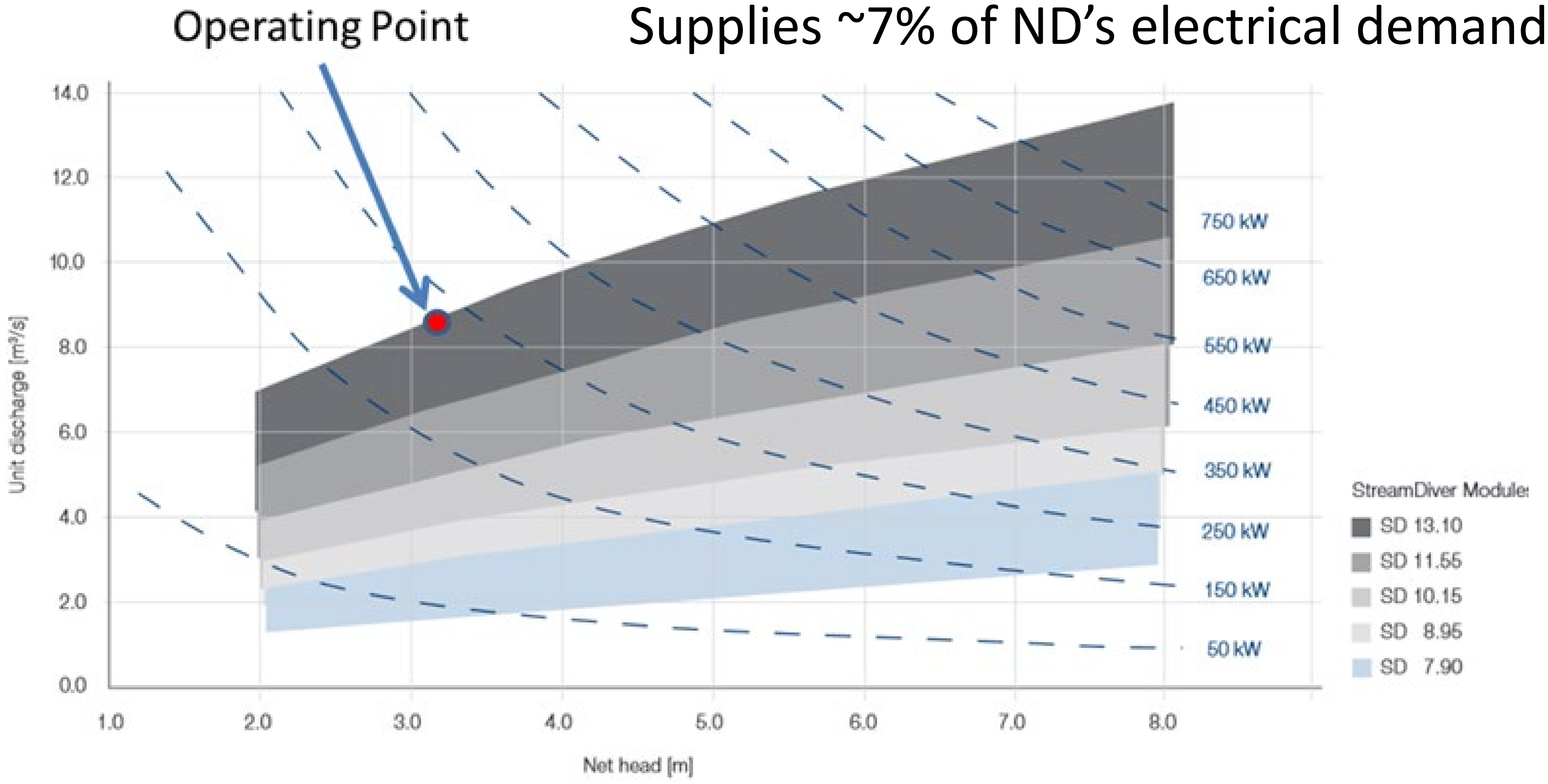


ND Hydropower Plant
Climate Change Assessment

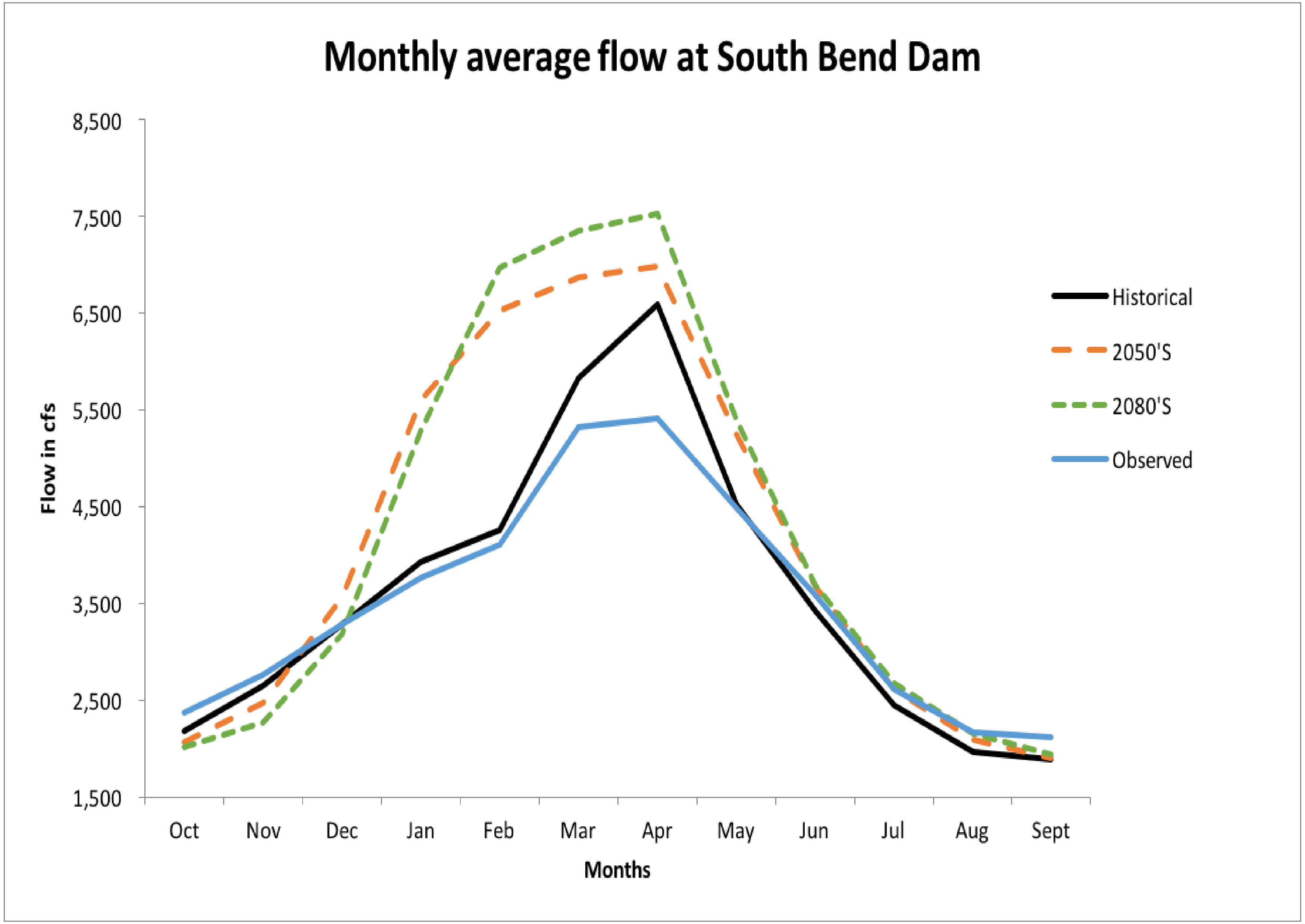
Benavente, M., K. Byun, A. F. Hamlet, 2016: Effects of Climate Change on the Proposed St. Joseph River Hydropower Plant for the University of Notre Dame, Independent report prepared for the Notre Dame Department of Utilities and Maintenance.

Approximate Operating Point for Voith Streamdiver Low-Head Hydropower Turbine
(10 turbines installed in ND plant)

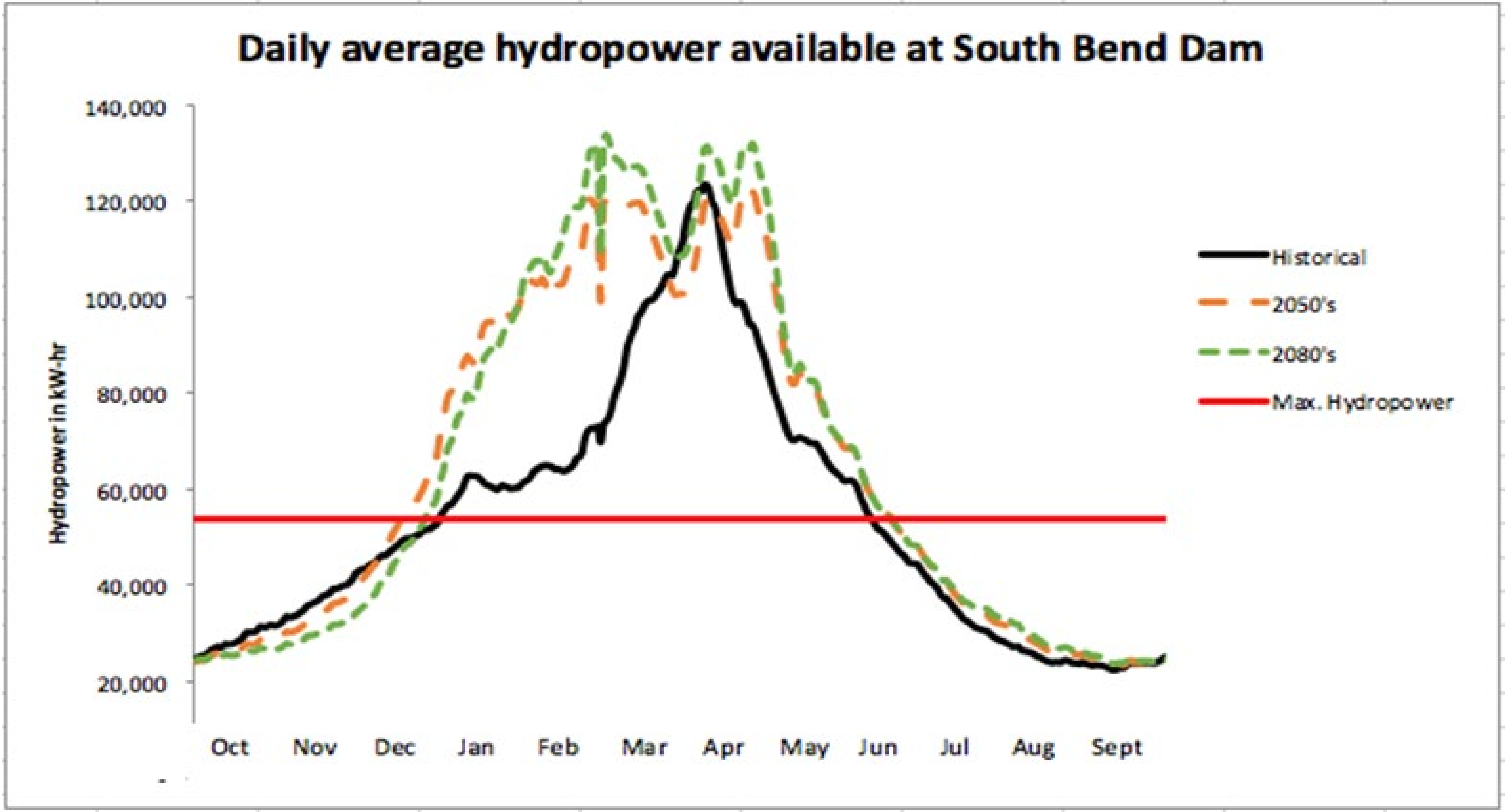
Supplies ~7% of ND's electrical demand



Historical and Future Streamflow Simulated by the VIC Hydrology Model (RCP8.5 Scenario)



Simulated Historical and Future (RCP8.5 Scenario)Potential Hydropower Production



Developing A Non-Stationary Framework for:

a) Analyzing the Performance of Existing Infrastructure

b) Estimating Design Standards for New Infrastructure

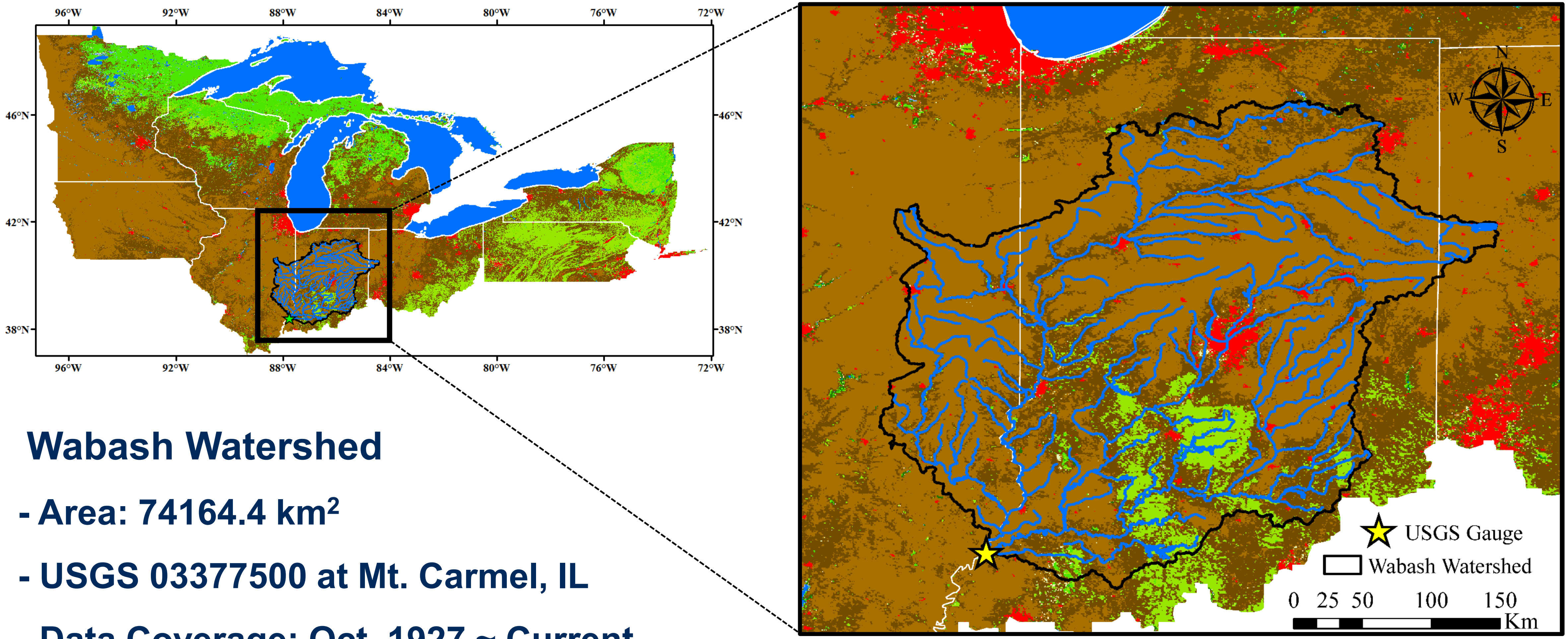
Byun, K., A. F. Hamlet, 2020: A risk-based analytical framework for quantifying non-stationary flood risks and establishing infrastructure design standards in a changing environment, Journal of Hydrology, 584, 125575, https://doi.org/10.1016/j.jhydrol.2020.124575

Given the observed changes in the historical record and projections for the future, it is evident that new paradigms are needed for the management of natural resources and the design of infrastructure in a non-stationary environment:

"Stationarity is dead, whither water management?"
(Milly et al. 2008)

Milly, A. P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Zbigniew, W., Lettenmaier, D. P., et al. (2008). Stationarity Is Dead : Stationarity Whither Water Management ? Science, 319(5863), 573–574. https://doi.org/10.1126/science.1151915

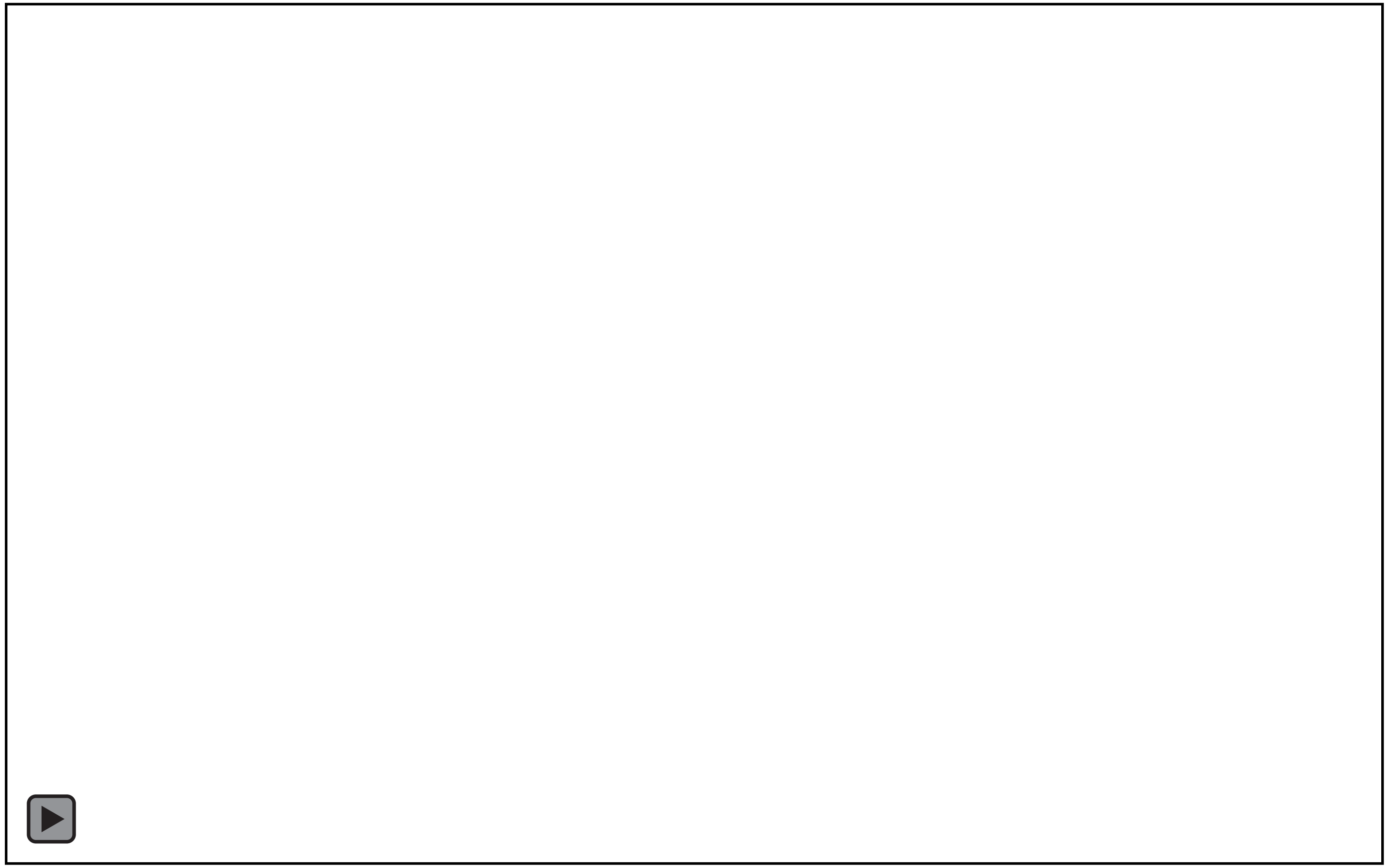
Example Watershed Analysis



- **Wabash Watershed**
  - **Area: 74164.4 km^2**
  - **USGS 03377500 at Mt. Carmel, IL**
  - **Data Coverage: Oct. 1927 ~ Current**

A Unique PDF for Each Year of the Design Lifespan Based on Future Projections

- **Comparison of PDFs between historical and future 30-yr window**



- Monte-Carlo simulation by pdf of specific time window

- Initial future periods look very similar to the historical distribution

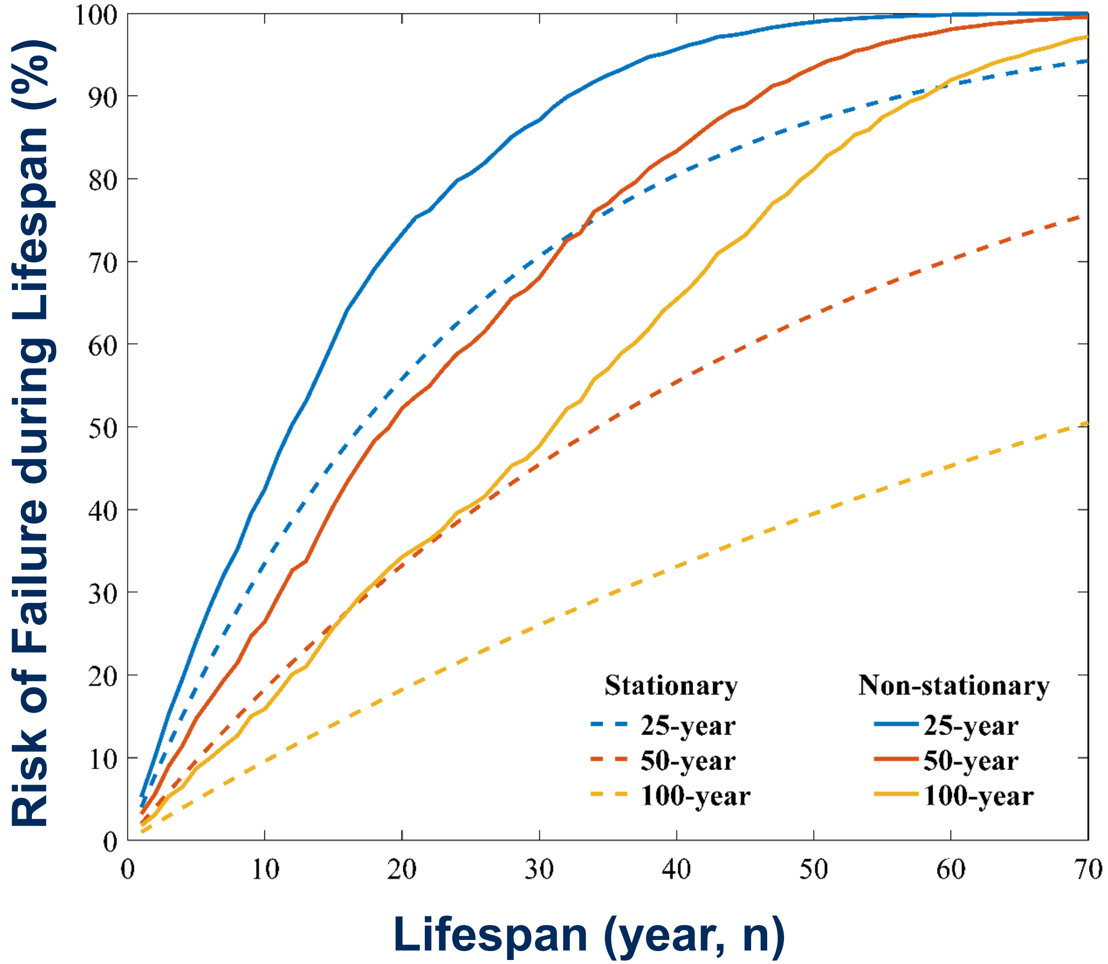
- Non-monotonic shifts between years

- Significant changes at later periods

101% in 100-yr event at 2086

Estimating the Risk of Failure as a Function of Design Lifespan

- **Evaluation of Risk of Failure during the Lifespan of an Existing Structure (Probability of at least one event above design standard during the design lifespan)**



- Designed by different level of design standards (e.g. 25, 50 and 100-yr) from historical distribution

- Stationary approach (historical distribution):

$$\mathbf{1 - (1 - q)^n}$$

$$q : probability\ of\ exccedance\ during\ a\ year$$

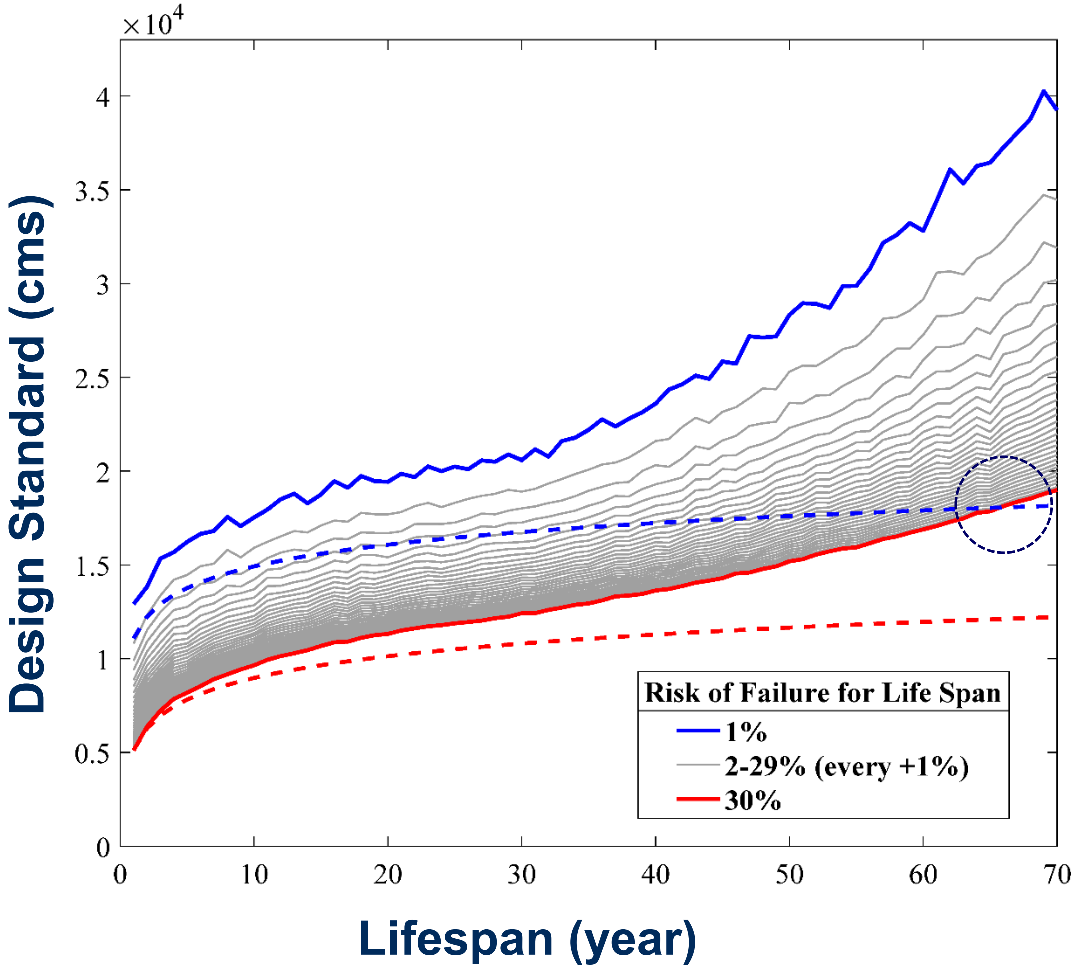
- Non-stationary approach (super ensemble):

$$\mathbf{1 - \prod_{t=1}^{n}(1 - q_t)}$$

$$q_t = \frac{\#\ Events\ above\ design\ standards}{\#\ Realizations}$$

Inverting the Problem to Estimate Design Standards for New Infrastructure.

- **Design Standards for New Structure based on Different Levels of Risk of Failure**



- **Suggested design standards by different level of risk of failure (e.g. %1 ~ %30)**

- **Non-stationary approach (super ensemble): designed standard that closes the following form with given level of risk of failure:**

$$Risk = 1 - \prod_{t=1}^{n}(1 - q_t)$$

- **Significant differences compared to stationary approach with longer lifespan**
  e.g. 30% level of risk (non-stationary) = %1 level of risk (stationary)

Ultra Extremes:
Learning to Cope with an Emerging Threat

Extreme Summer Storms are Causing Unprecedented Damage to Urban and Suburban Infrastructure in the Midwest, Southern Canada, and the Great Plains

Toronto August, 2005

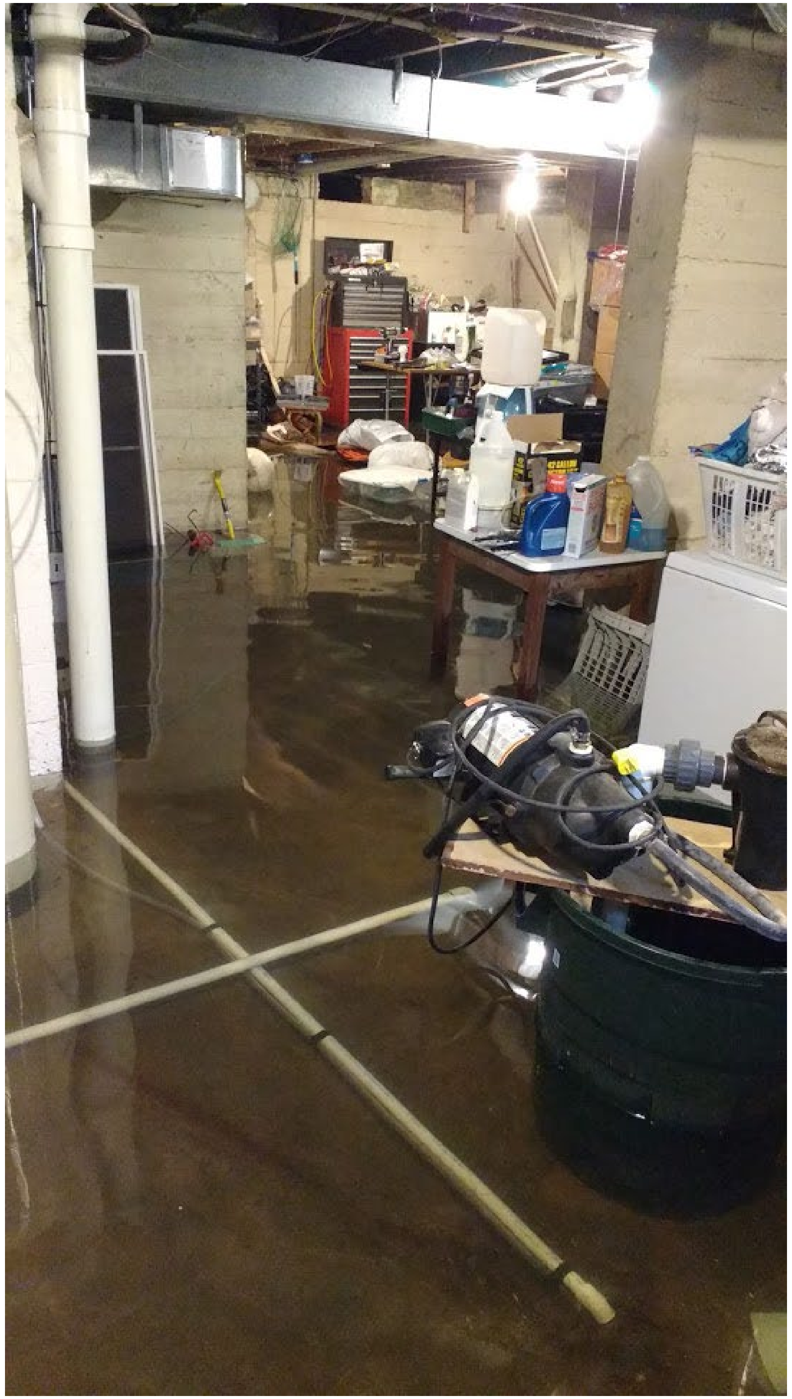
Southern Alberta June, 2013

Flooding in southern Alberta in June, 2013 was reported as the single most costly natural disaster in Canada's history, with more than $1.74 billion $CA in insurance damages. Insurance losses in the Toronto metropolitan area in July, 2013 added another $940 million $CA in insurance damages, the most expensive natural disaster in Ontario's history (Insurance Bureau of Canada, 2013).

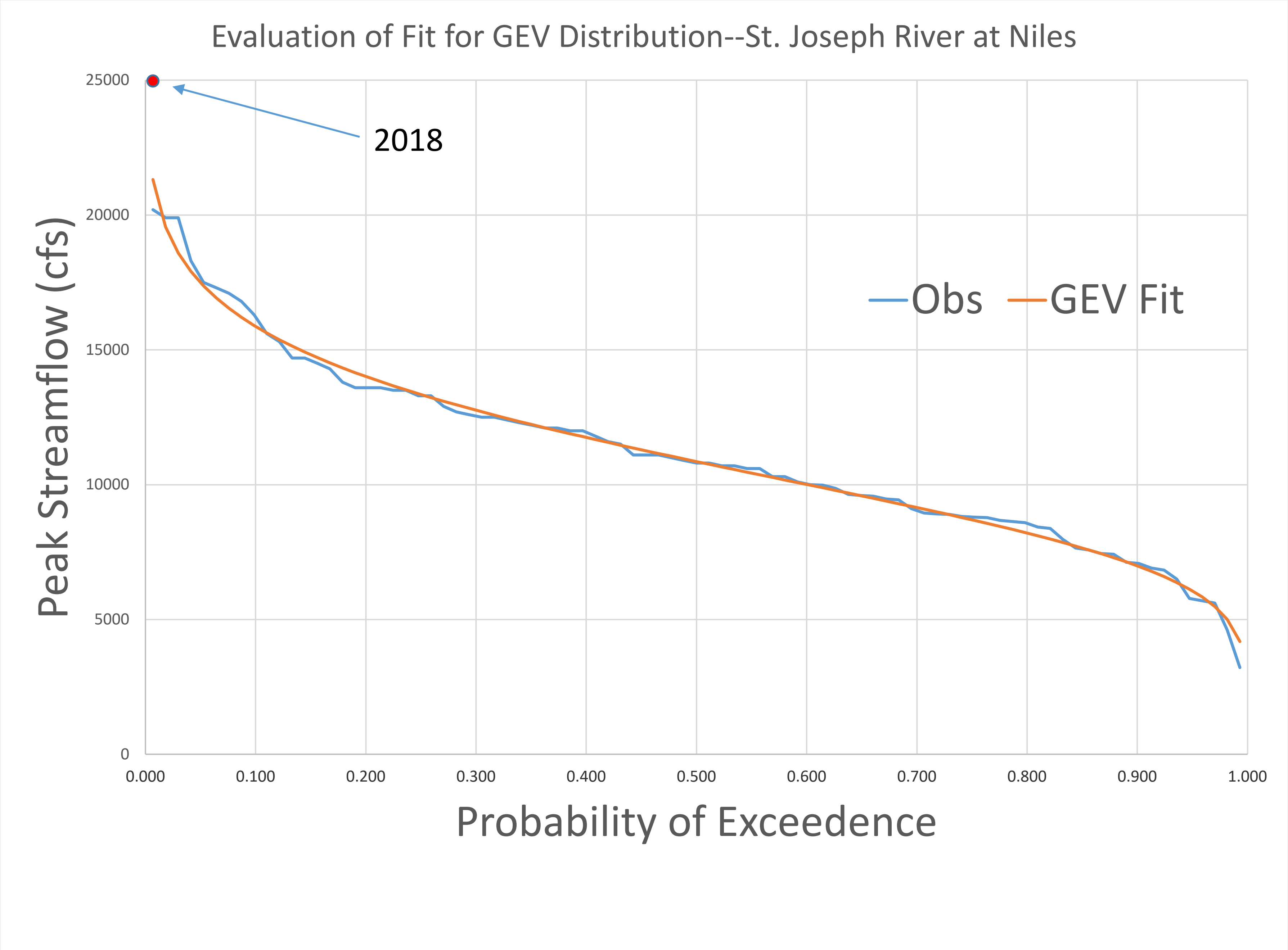
Aftermath of record-breaking rainfall on August 15, 2016, (~500 year event)

Canoeing on Nokomis Park, August 16, 2016

Record-breaking flooding in the St. Joseph River at South Bend, Feb 21, 2018, due to an extreme rain-on-snow event (~2400-yr event)



~8,000 gallons
of groundwater
in my
basement!


Evaluation of Fit for GEV Distribution--St. Joseph River at Niles
2018
Obs
GEV Fit
Peak Streamflow (cfs)
Probability of Exceedence
25000
20000
15000
10000
5000
0
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000

Conclusions:

- Climate change is projected to bring major changes in Midwest climate. We will need to learn to live in a warmer and wetter environment in fall, winter, and spring, but the late summer may be warmer and drier.

- Climate change will bring profound challenges to sustainable environmental management and the design of engineering infrastructure.

- Climate change will also bring opportunities to adapt and, in some cases, even improve the performance of natural and human systems.