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Future Spatiotemporal Patterns of Corn Soil Organic Carbon Use Efficiency in the U.S. Corn Belt

Insights from CMIP5 Projections (2010-2099)

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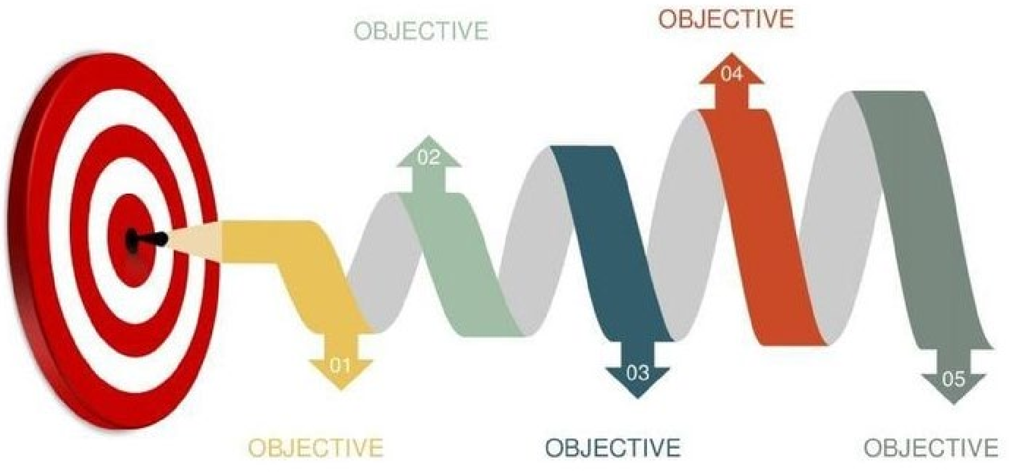
Objective

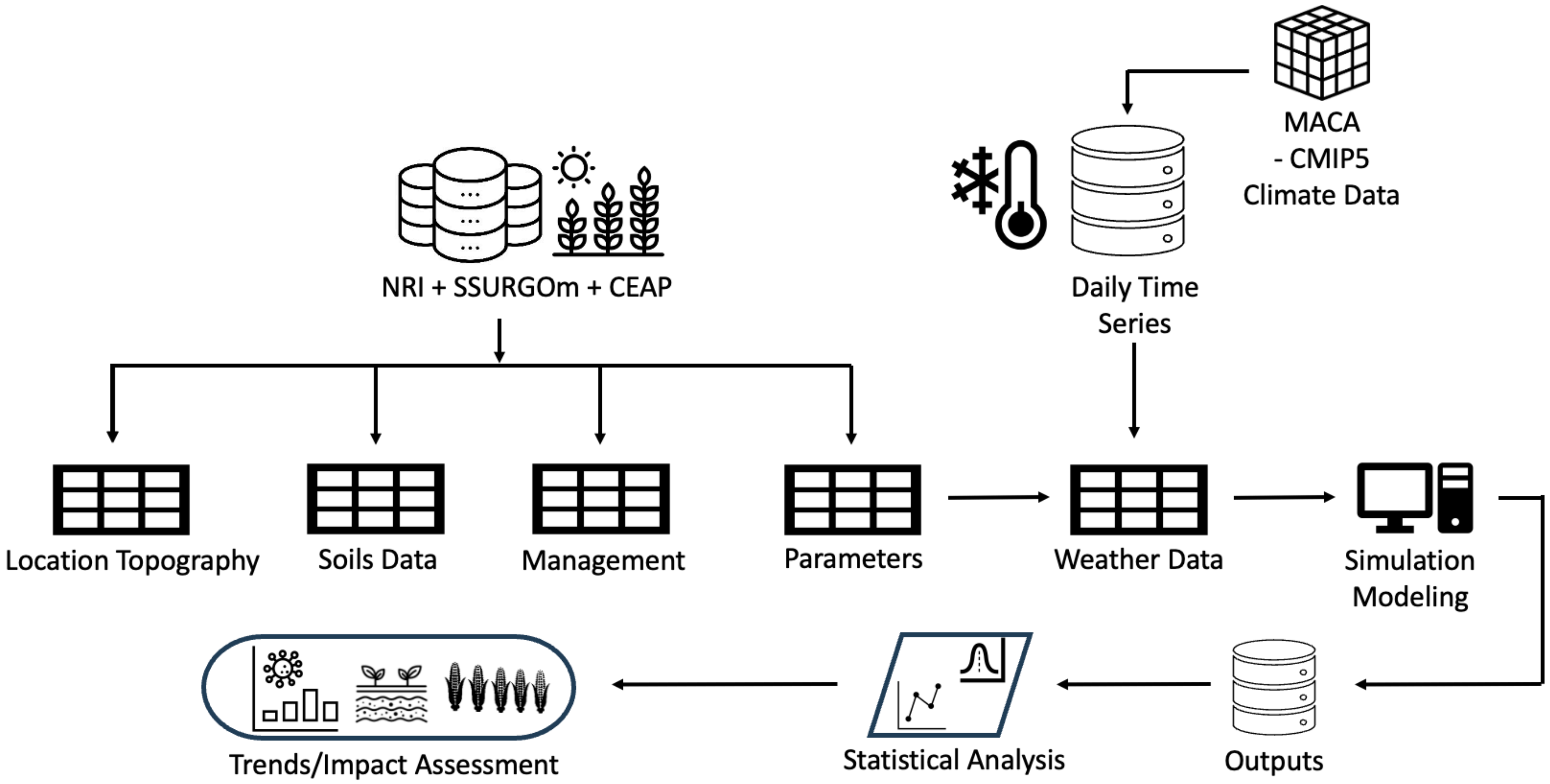


To assess how future climate change will affect corn yield and soil organic carbon (SOC) dynamics in the U.S. Corn Belt.

We employ the process-based APEX model as a simulation framework
Linking climate drivers to yield and SOC responses over a century.

We integrated temporal trend analysis, combining Mann–Kendall test and Sen's slope estimator with spatial autocorrelation methods (Moran's I and Getis–Ord Gi*)
To characterize direction and magnitude of long-term changes and spatial clustering.

MODELING FRAMEWORK



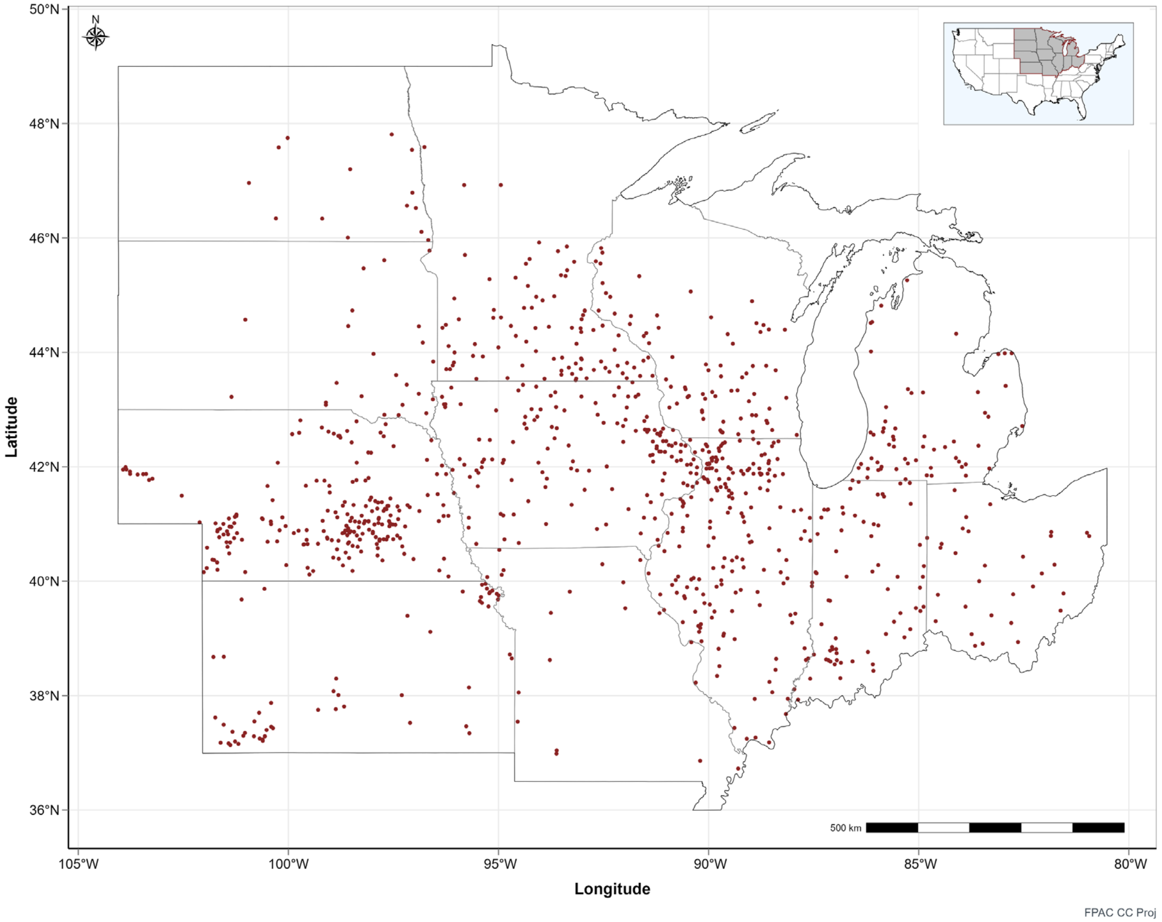
Location & Duration

Spatial scale:

- Corn Belt
- 1020 Sites

Time period

- Historical: 1971–2005
- Future: 2010 to 2099



G C M

GLOBAL CIRCULATION MODELS

R C P

Representative Concentration Pathways

M A C A v 2 - M E T D A T A

University of Idaho

HadGEM2-ES365: Met Office Hadley Centre (UK)

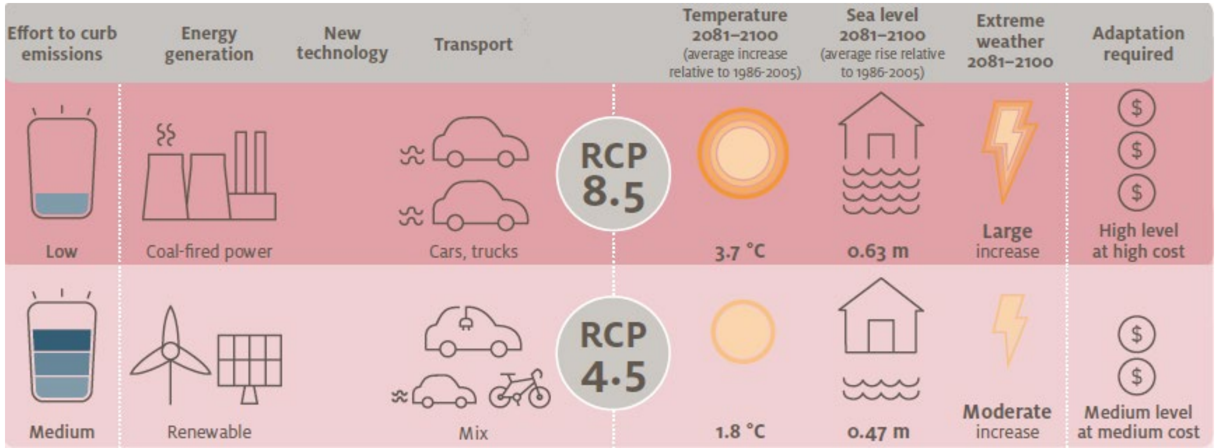
PSL-CM5A-MR: Institut Pierre Simon Laplace (FR)

MRI-CGCM3: Meteorological Research Institute (JP)

NorESM1-M: Norwegian Climate Center (NO)

CCSM4: National Center of Atmospheric Research (US)

CNRM-CM5: National Centre of Meteorological Research and European Centre for Advanced Research and Training (FR)



S O C U E

SOC Use Efficiency (kg yield / kg C):

$$SOCUE_t = \frac{Y_t}{\Delta SOC_t}$$

How many kilograms of corn grain you get for every kilogram of carbon that your soil is above or below its historical average

- For every 1 kg of carbon surplus, you get X kg of yield (+).
- For every 1 kg of carbon deficit, you are extracting X kg of yield (-).

Change in SOC from historical mean (Mg C/ha):

$$\Delta SOC_t = SOC_t - \overline{SOC}_{h\,(\mathbf{1985-2016})}$$

Temporal Analysis

The **Mann–Kendall** trend test is a non-parametric statistical method used to detect monotonic trends in time series data.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i)$$

- A large positive S value indicates an upward trend.
- A large negative S value indicates a downward trend.
- An S value close to zero suggests no monotonic trend.

The Mann-Kendall statistical significance of the trend is indicated through the presence of the dots

Temporal Analysis

Sen's slope is a non-parametric method used to estimate the magnitude (rate) of a linear trend in a time series.

Calculate Slopes

$$m_{ij} = \frac{x_j - x_i}{t_j - t_i}$$

Find the Median of These Slopes:

$$m = \text{Median}(m_{ij}) \quad \text{for } 1 \leq i < j \leq n$$

- Positive Sen's slope indicates an increasing trend.
- Negative Sen's slope indicates a decreasing trend.
- Slope of zero indicates no trend.

The value of the Sen’s slope gives the quantitative **rate of change** per decade (color scale).

Spatial Analysis

Global Moran's I: Measures the overall spatial autocorrelation across an entire area.

$$I = \frac{N}{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}} \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

Ranges from -1 to +1

- $I > 0$: Positive Spatial Autocorrelation (Clustering)
- $I < 0$: Negative Spatial Autocorrelation (Dispersion/Checkerboard Pattern)
- $I \approx 0$: No Spatial Autocorrelation (Random Distribution)

- N: The number of spatial units (sites/hexagons).
- x_i: The value of the variable at location i (e.g., Sen's slope of SOCUE).
- $\bar{x}$: The mean of the variable across all locations.
- w_{ij}: The spatial weight between location i and location j. This defines what "neighbor" means (e.g., shared border, within a certain distance).
- $\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}$: The sum of all spatial weights (often denoted as S_0).

Spatial Analysis

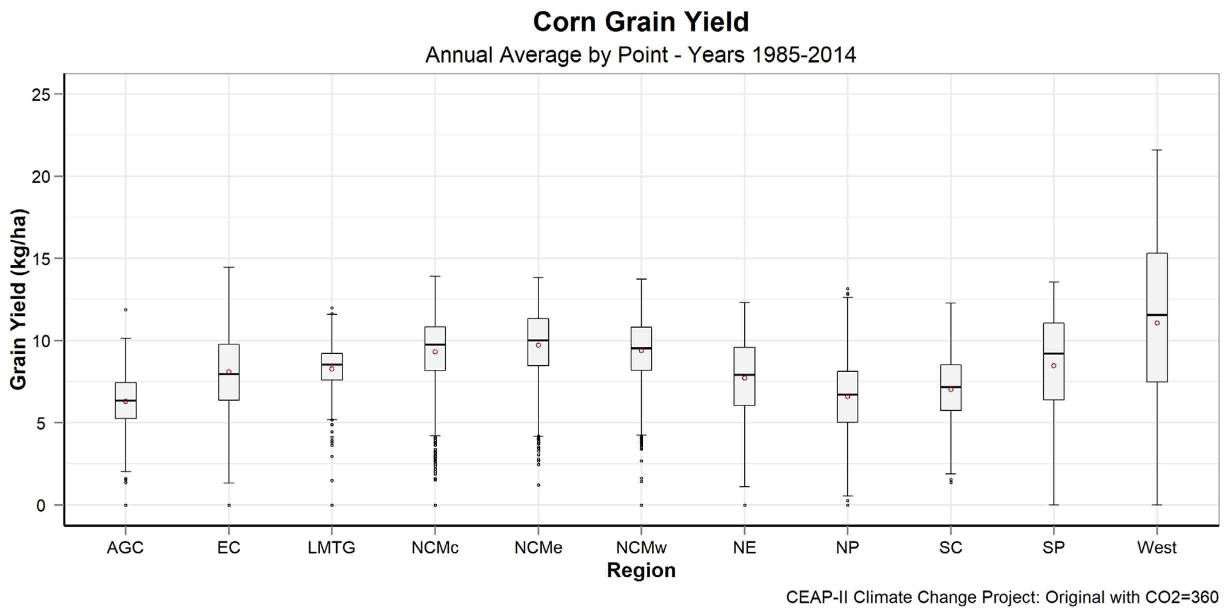
Getis–Ord Gi* is a local spatial statistic used to identify statistically significant areas where high or low values cluster spatially given a specified neighborhood structure.

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}}$$

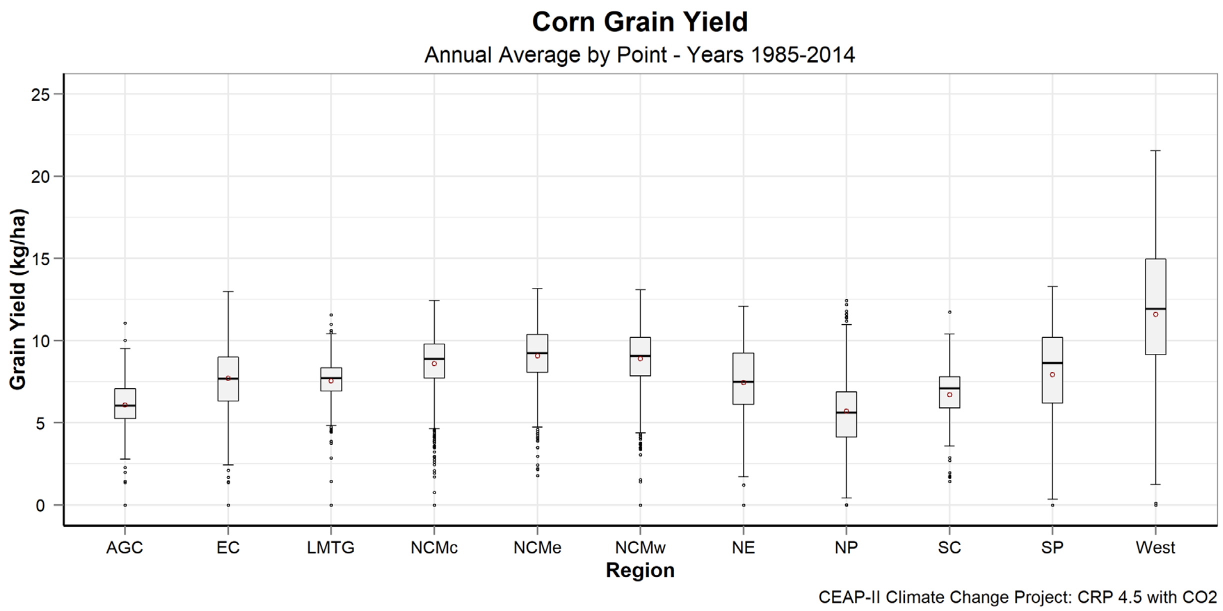
Positive significant Gi*: i is in a neighborhood of high values (hotspot).
- Negative significant Gi*: i is in a neighborhood of low values (coldspot).
- Non-significant: local values are not unusually concentrated given the spatial structure.

For each location i, Gi* compares the sum of values in i's neighborhood (including i itself) to what would be expected under spatial randomness, accounting for the number/weights of neighbors.

Corn Yield Comparison by Region

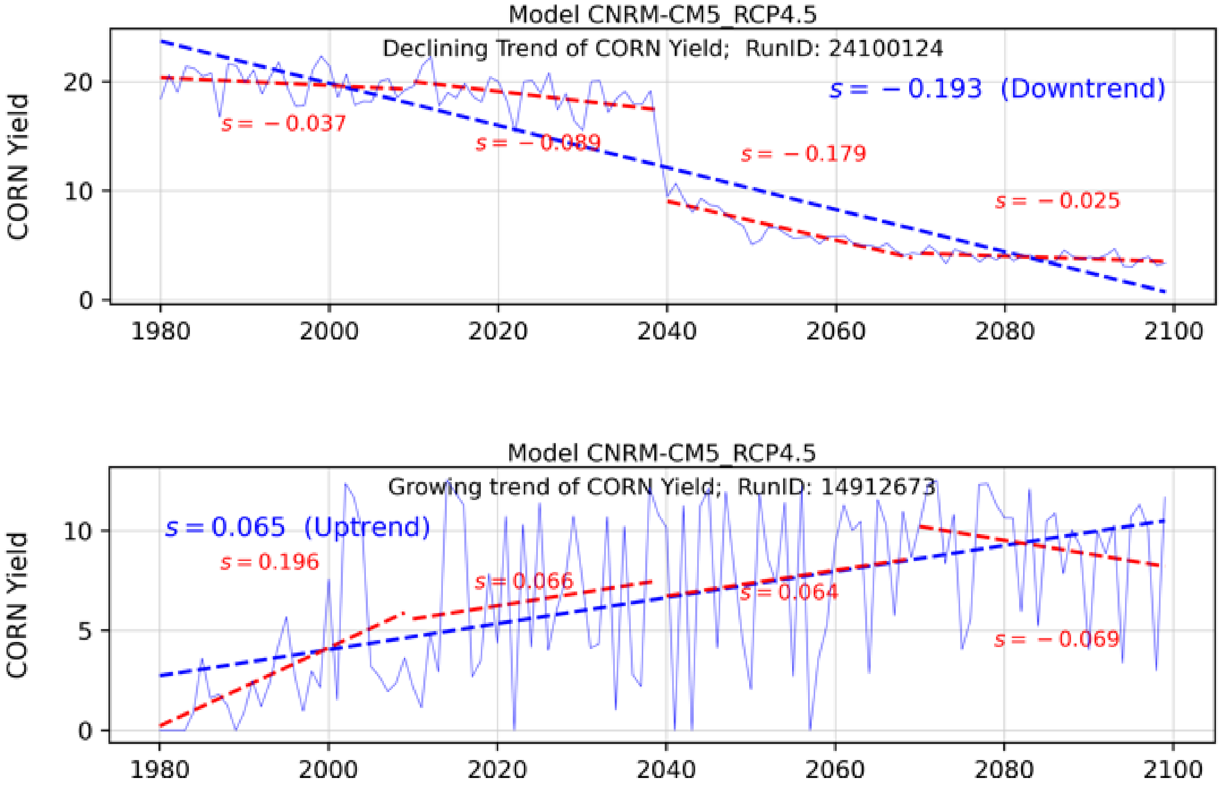


CEAP Weather Data

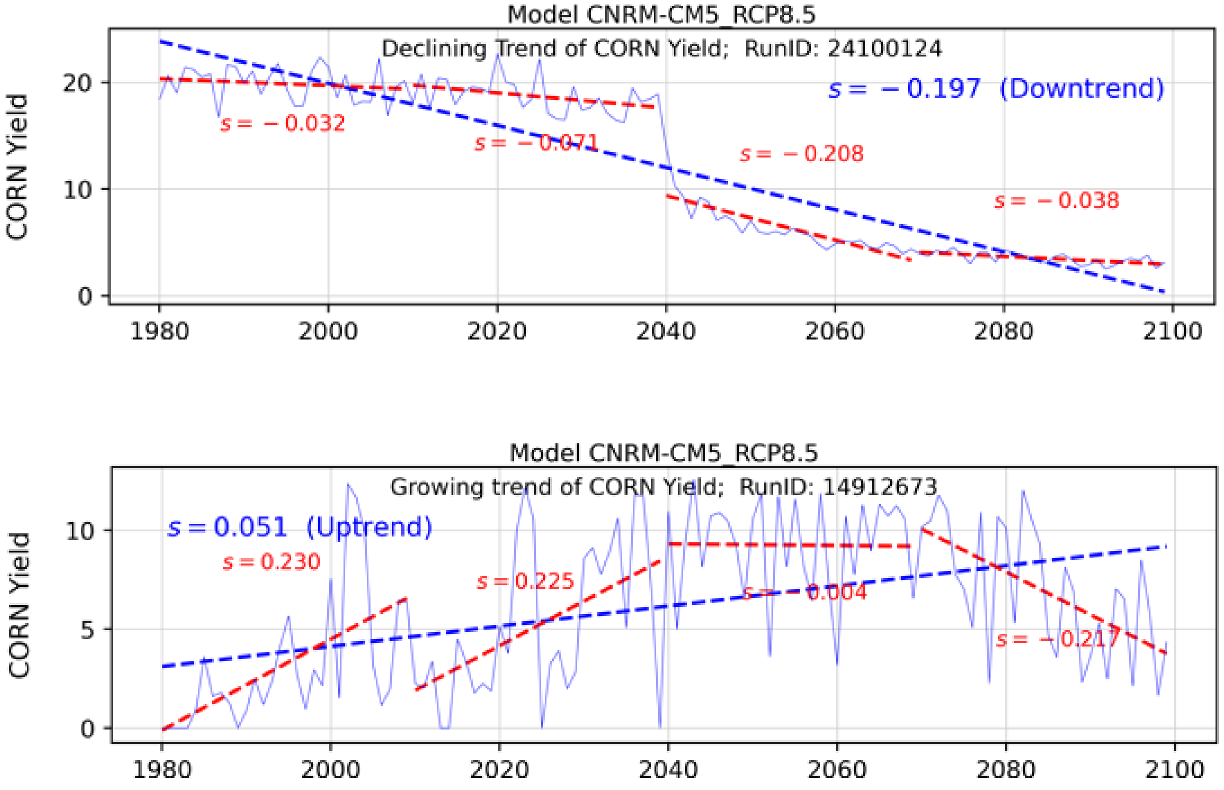


Historical MACA Data

Corn Yield Trends

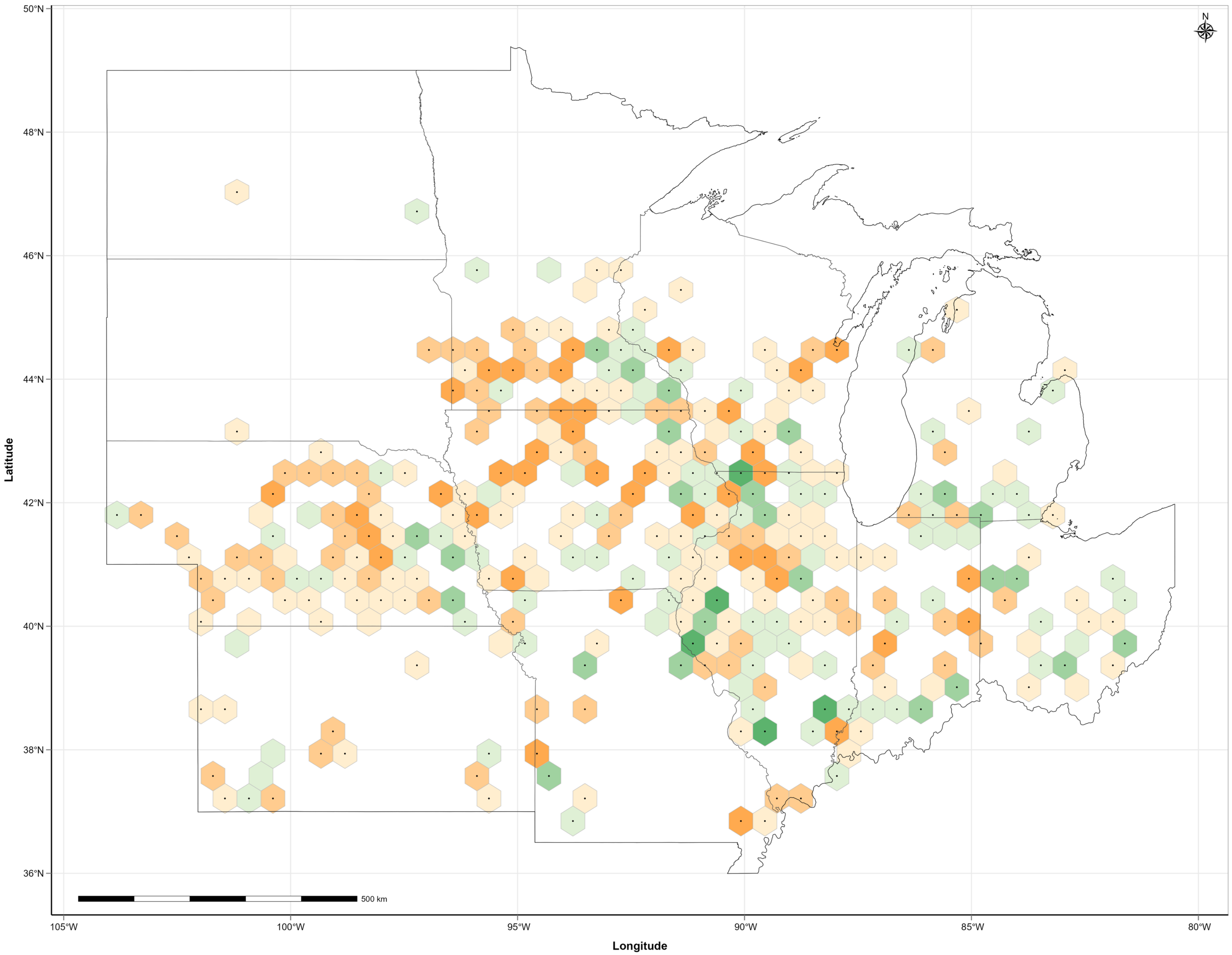


CNRM-CM5 + RCP – 4.5



CNRM-CM5 + RCP – 8.5

SOC
RCP – 8.5



Mann-Kendall

Statistical significance of the trend

Not Statistically significant

Statistically Significant

Sen's Slope

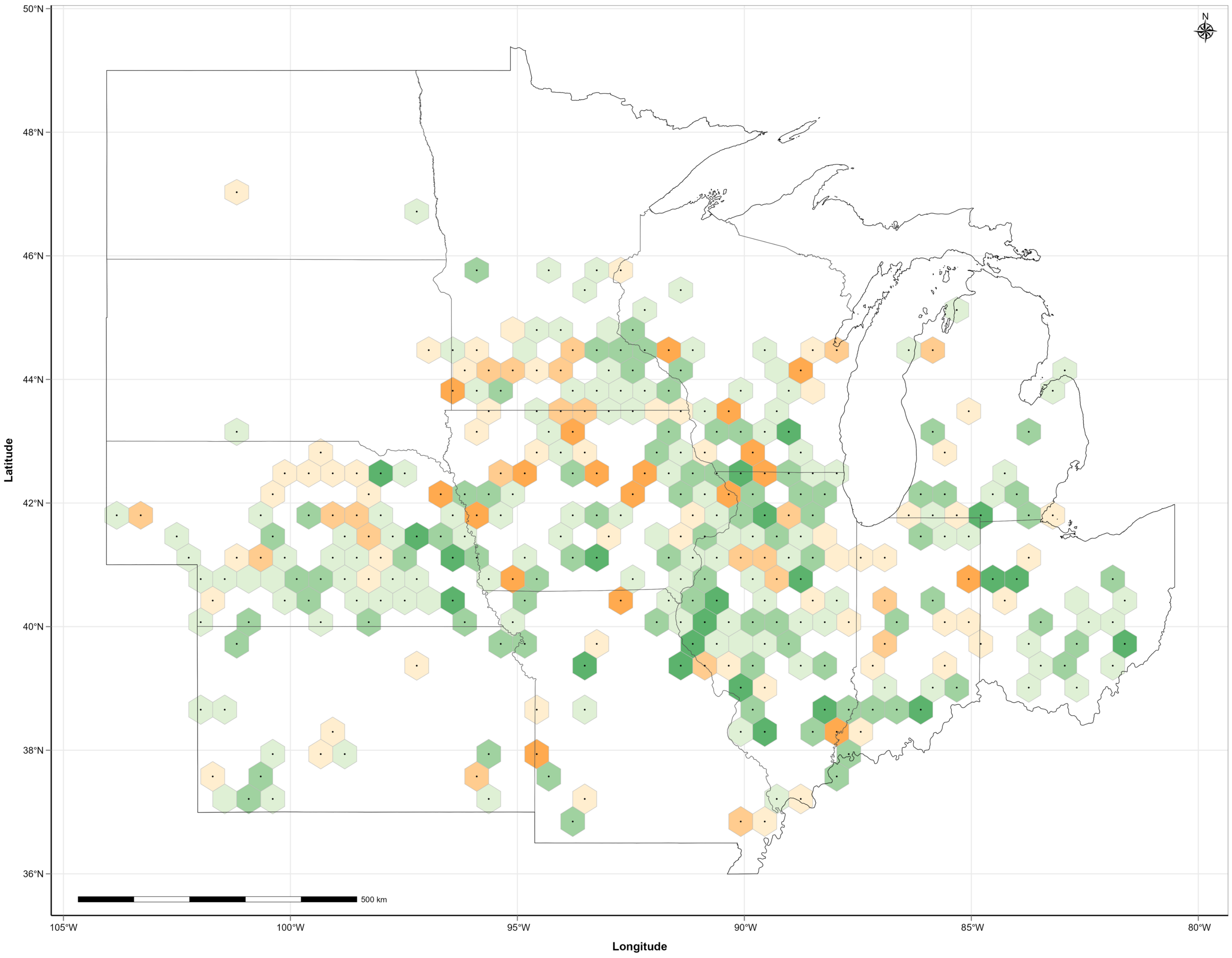
Rate of change per decade

SOC (kg/ha per Decade)

-3000 -2000 -1000 0 1000 2000 3000

S O C

RCP – 4.5



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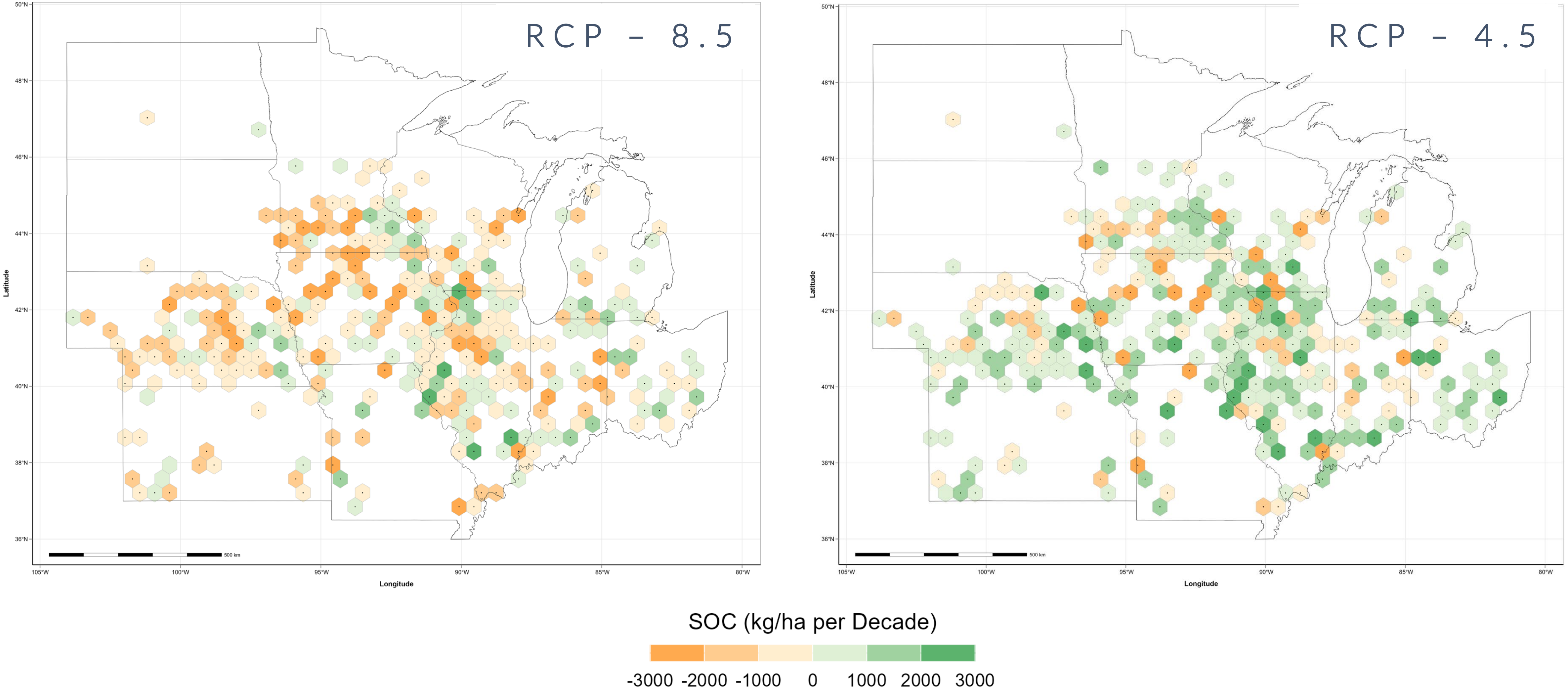
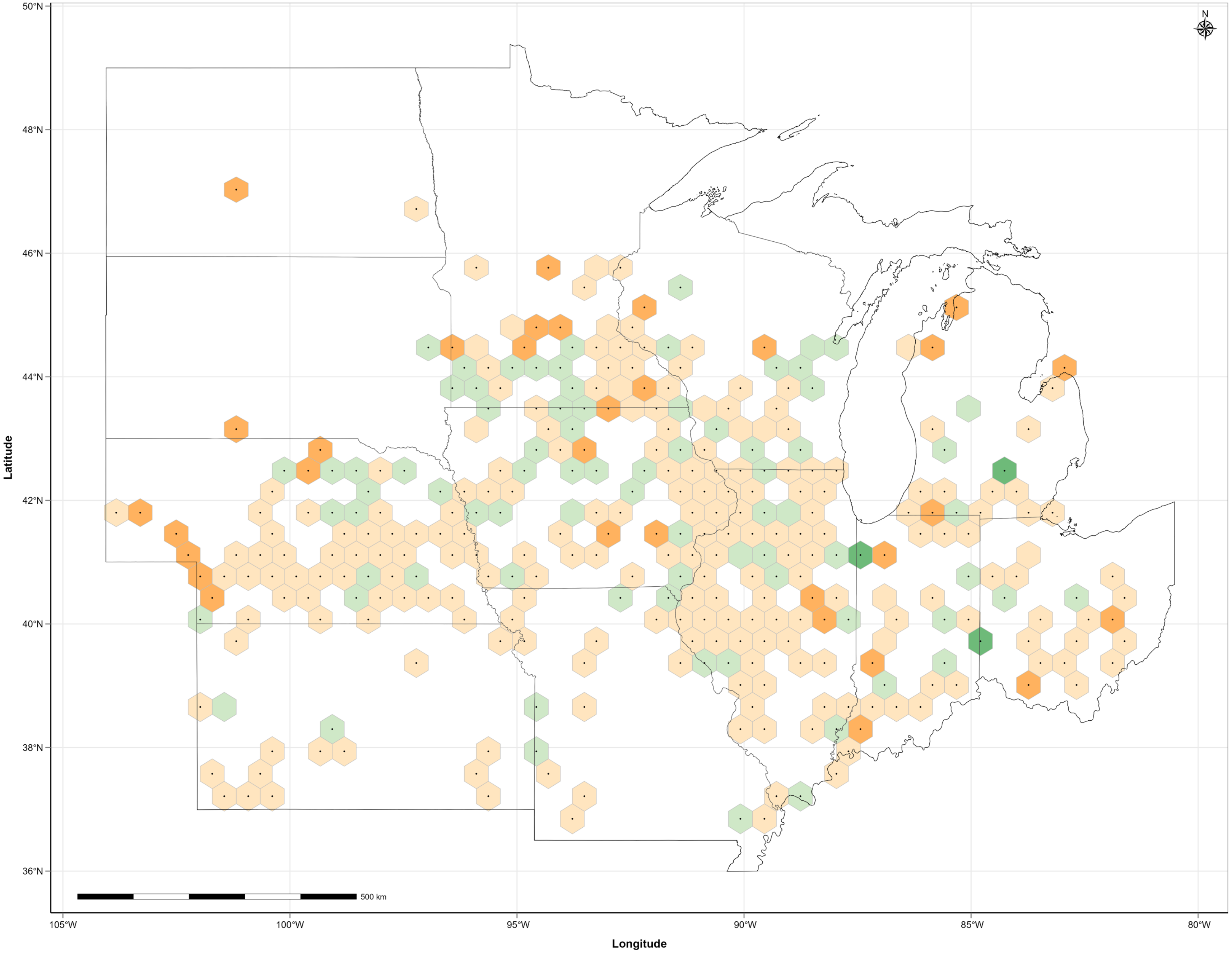
S O C


RCP – 8.5
RCP – 4.5
Latitude
Longitude
50°N
48°N
46°N
44°N
42°N
40°N
38°N
36°N
105°W
100°W
95°W
90°W
85°W
80°W
500 km
SOC (kg/ha per Decade)
-3000 -2000 -1000 0 1000 2000 3000

SOCUE

RCP – 8.5



Mann-Kendall

Statistical significance of the trend

Not Statistically significant

Statistically Significant

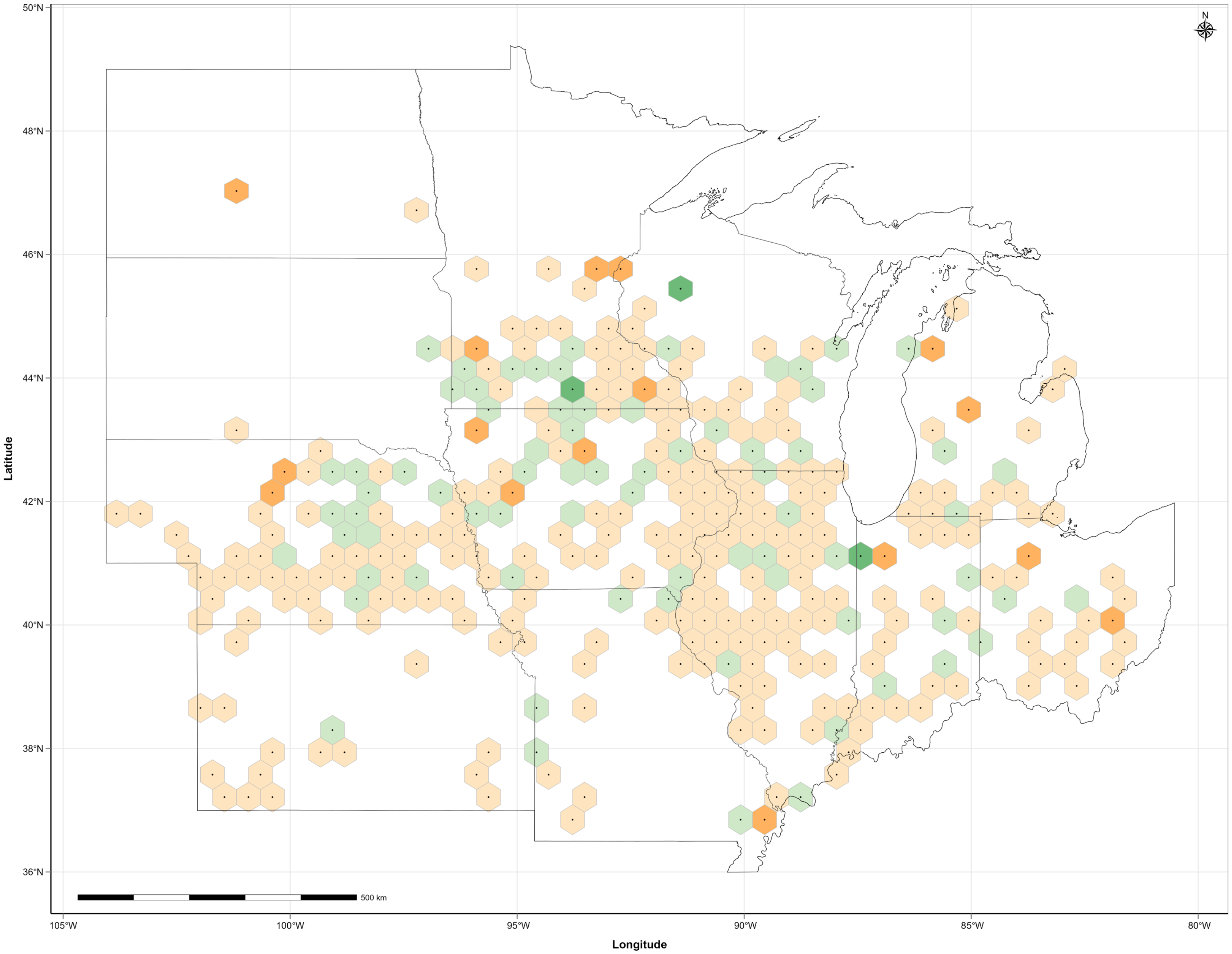
Sen's Slope

Rate of change per decade

SOCUE (kg Y/kg C per Decade)

-1000 -500 0 500 1000

SOCUE
RCP – 4.5



Mann-Kendall

Statistical significance of the trend

- Not Statistically significant
- Statistically Significant

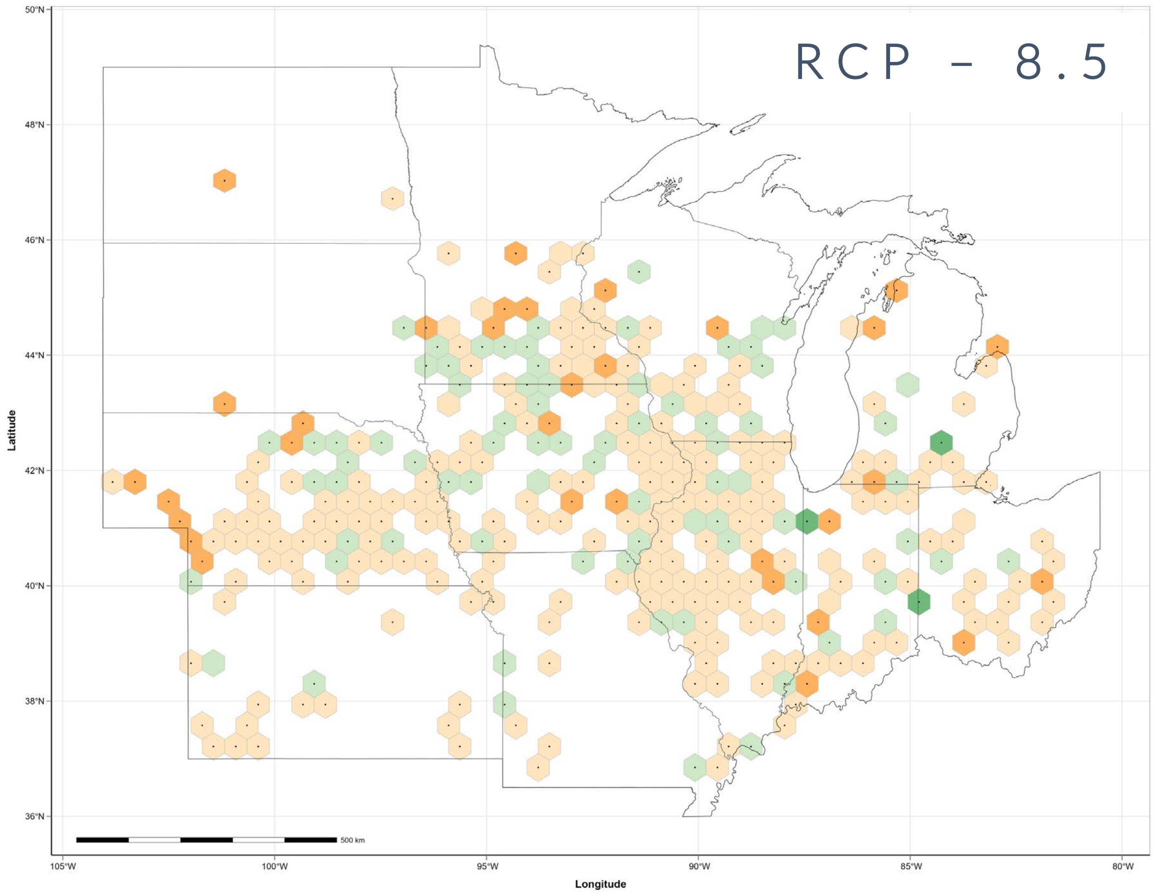
Sen's Slope

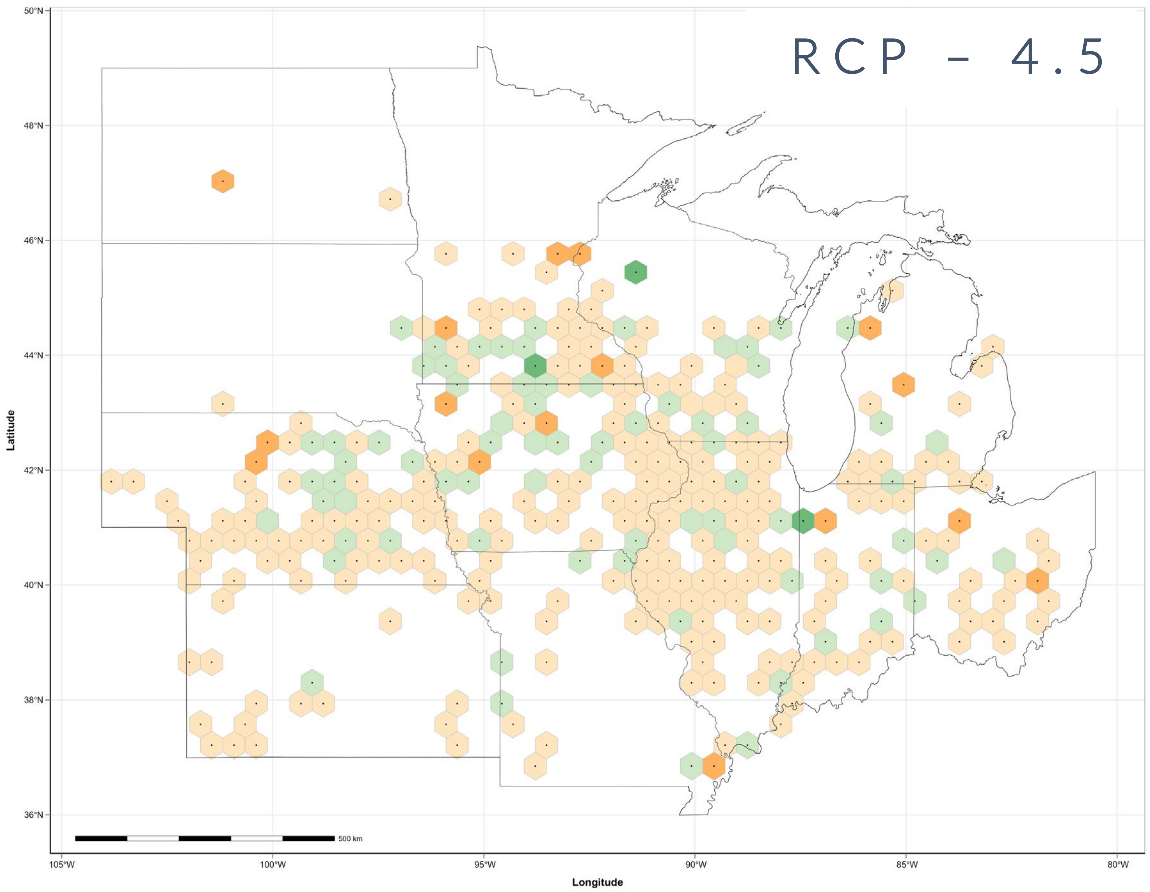
Rate of change per decade

SOCUE (kg Y/kg C per Decade)

-1000 -500 0 500 1000

SOCUE



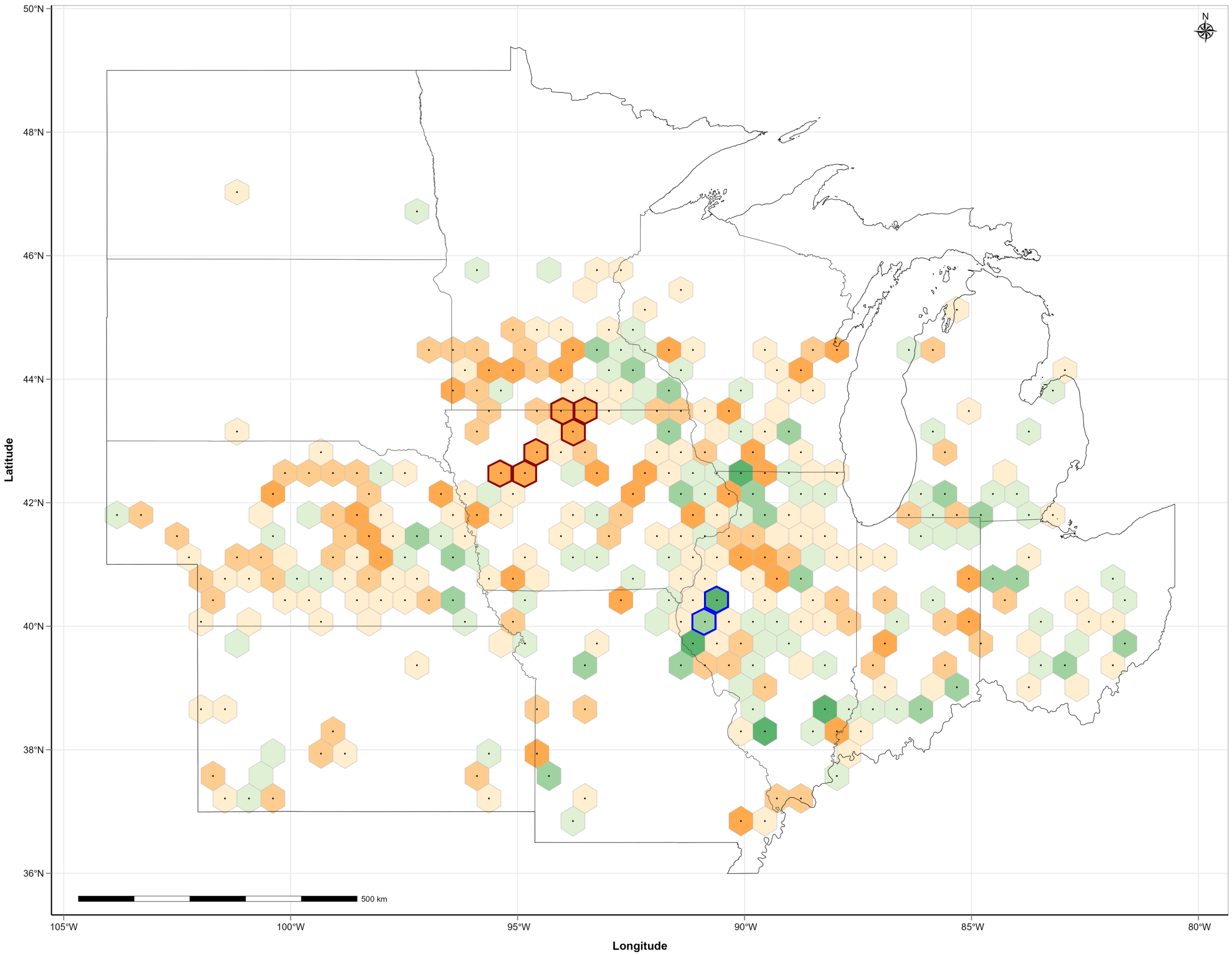


SOCUE (kg Y/kg C per Decade)

-1000 -500 0 500 1000

SOC

RCP – 8.5



Global Moran's I = - 0.040 (p = 0.803)

- I > 0: positive spatial autocorrelation
- I < 0: negative spatial autocorrelation
- I ≈ 0: spatial randomness

Getis Ord G*

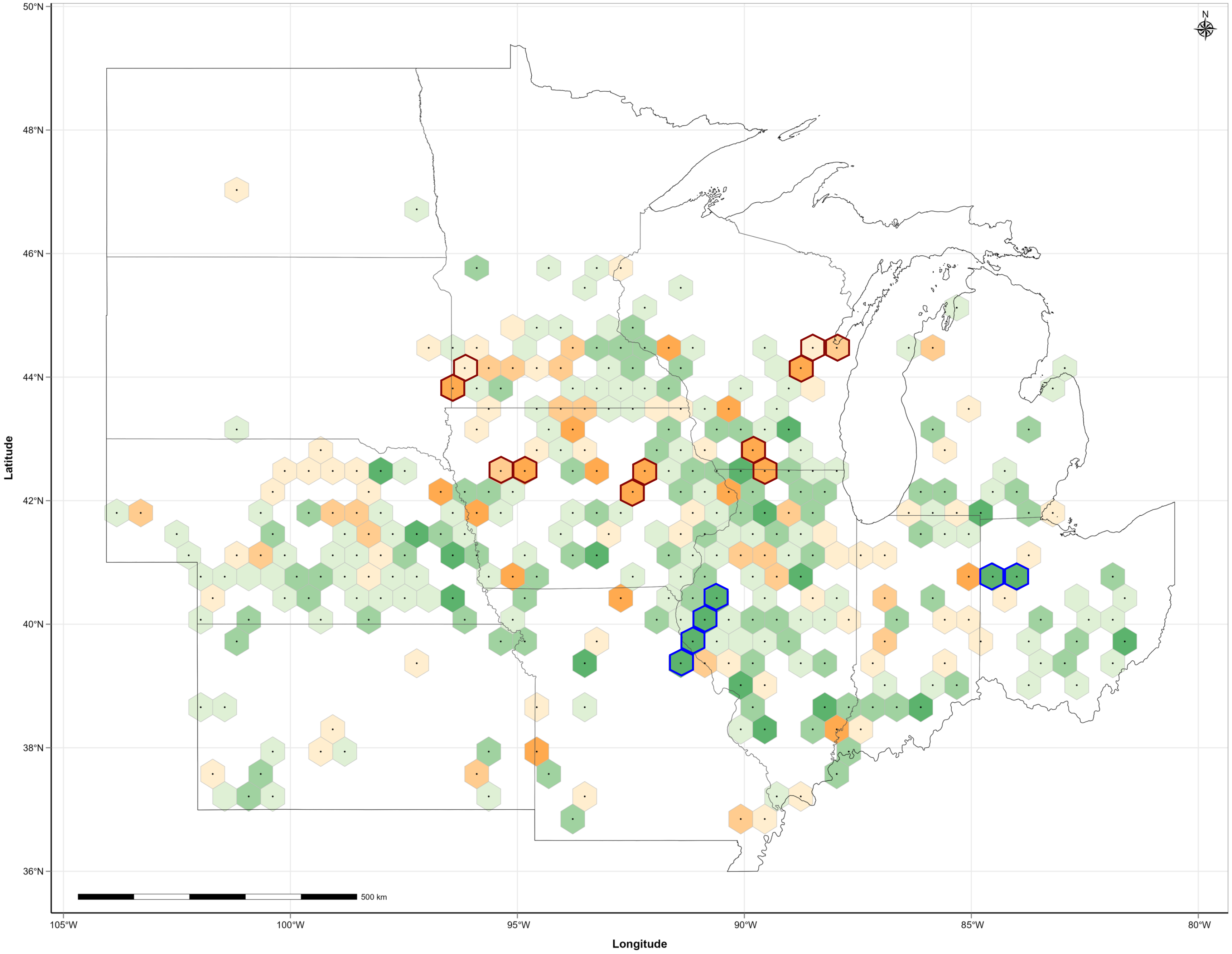
Identifies statistically significant hotspots

Hotspot (Significant positive Gi*)

Coldspot (Significant negative Gi*)

SOC

RCP – 4.5



Global Moran's I = 0.028 (p = 0.254)

- I > 0: positive spatial autocorrelation
- I < 0: negative spatial autocorrelation
- I ≈ 0: spatial randomness

Getis Ord G*

Identifies statistically significant hotspots

Hotspot (Significant positive Gi*)

Coldspot (Significant negative Gi*)

SOCUE
RCP – 8.5

Global Moran's I = 0.045 (p = 0.126)

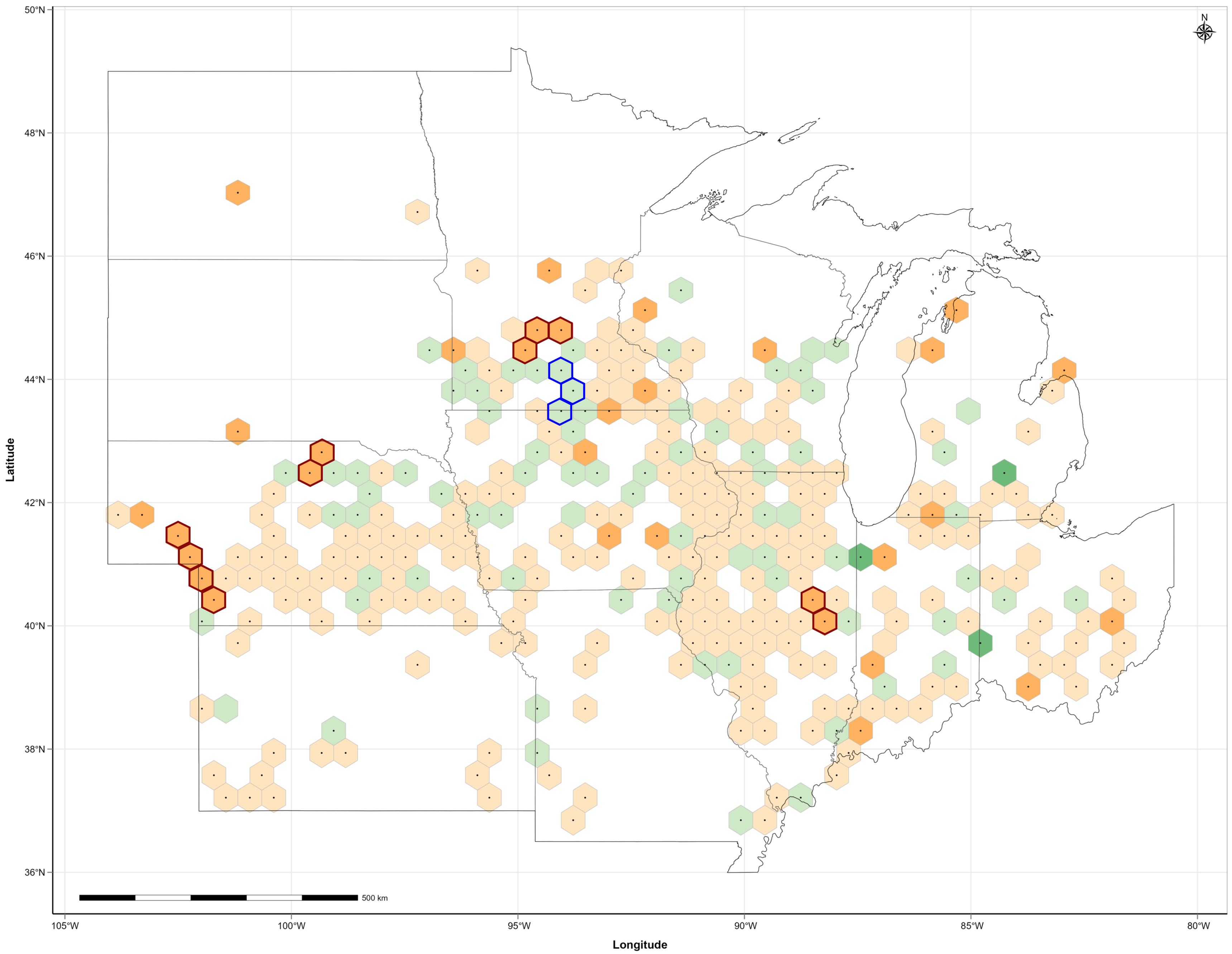
- I > 0: positive spatial autocorrelation
- I < 0: negative spatial autocorrelation
- I ≈ 0: spatial randomness

Getis Ord G*

Identifies statistically significant hotspots

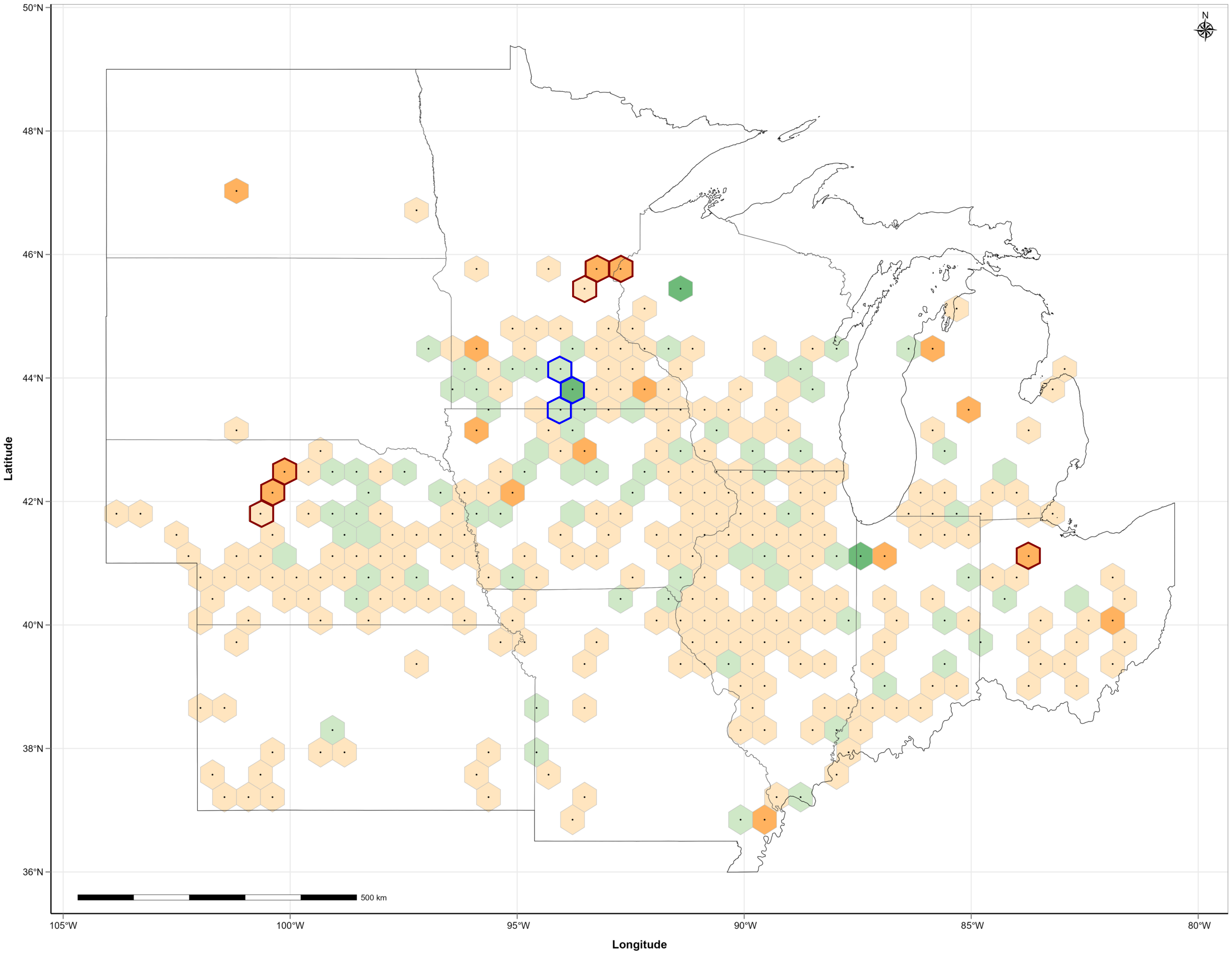
Hotspot (Significant positive Gi*)

Coldspot (Significant negative Gi*)



S O C U E

RCP – 4.5



Global Moran's I = - 0.028 (p = 0.713)

- I > 0: positive spatial autocorrelation
- I < 0: negative spatial autocorrelation
- I ≈ 0: spatial randomness

Getis Ord G*

Identifies statistically significant hotspots

Hotspot (Significant positive Gi*)

Coldspot (Significant negative Gi*)

Take Home Message

1

We developed a robust, multi-model, spatio-temporal framework to quantify how crop yields respond to soil organic carbon (SOC) under climate change, using process-based model outputs, and site-by-site normalization within hexagon regions.

2

Yield–SOC coupling is spatially heterogeneous and climate-sensitive.

3

Large-scale global clustering may be weak, but local hotspots and coldspots emerge.

4

Using SOCUE non-parametric trend tests, and local spatial statistics provides a transparent, reproducible pathway to target interventions that could improve productivity and soil carbon resilience under future climates.

2025 Colorado - SWAT Conference
20-24 October - Fort Collins, Colorado, USA

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N E X T

- Assess socioeconomic changes
- Management strategies
- Cause & Effect analysis