Statistical Evaluation of the North Dakota Cloud Modification Project using Rain Gauge Precipitation Observations

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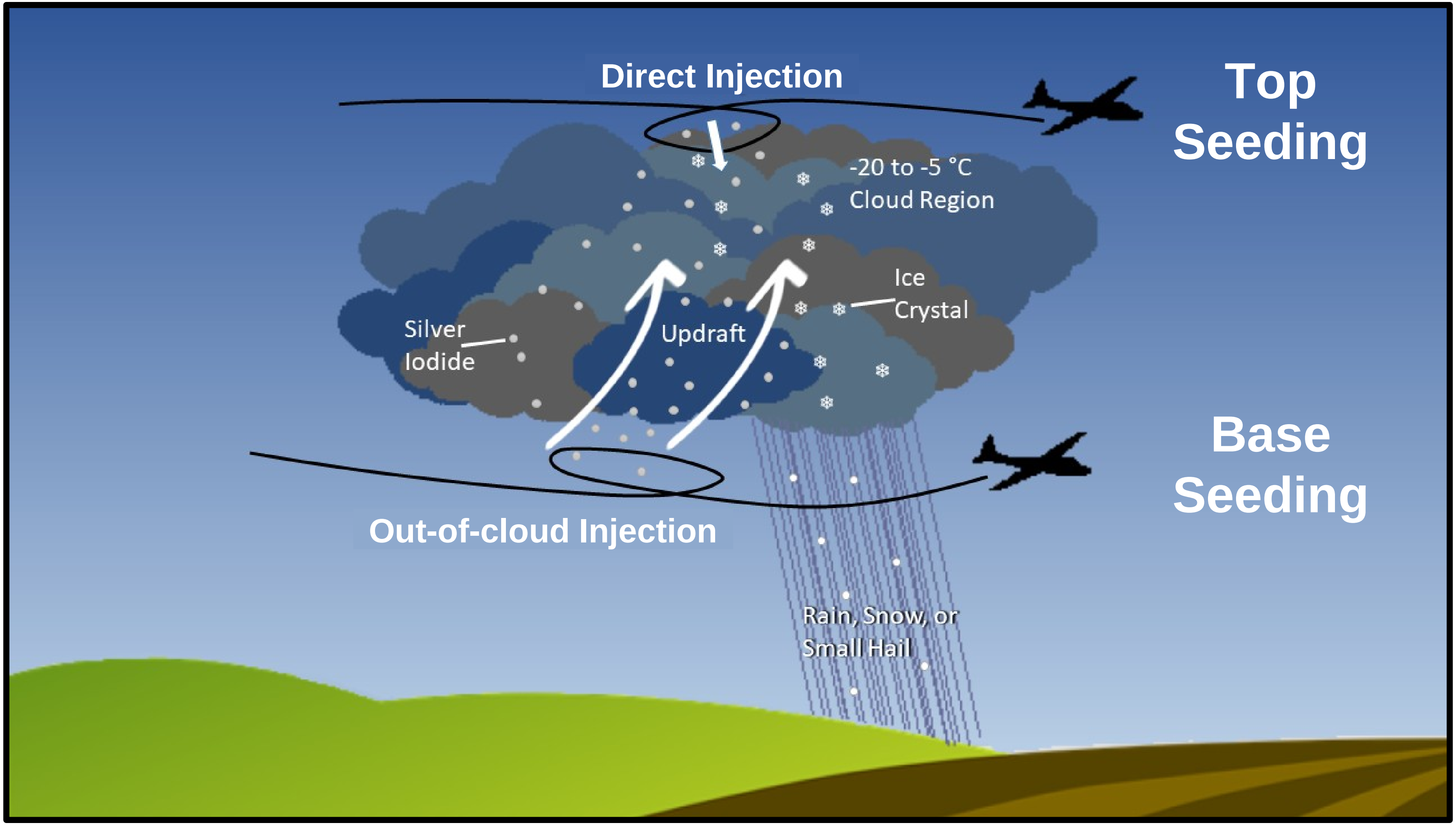
Background Information

- The North Dakota Cloud Modification Project costs the state of North Dakota approximately $1 million per year, which is approximately 13 cents per acre.
- The last previous statistical analysis related to the North Dakota Cloud Modification Project was conducted in 2005 (Wise, 2005).

*Green text discussed in previous presentation.

Basic Conceptual Model of Cloud Seeding



Research Project Objectives

- Determining the effectiveness of the North Dakota Cloud Modification Project at increasing rainfall within the project area.
- Provide seeding effectiveness at increasing rainfall for use in future economic cost/benefit ratio studies.

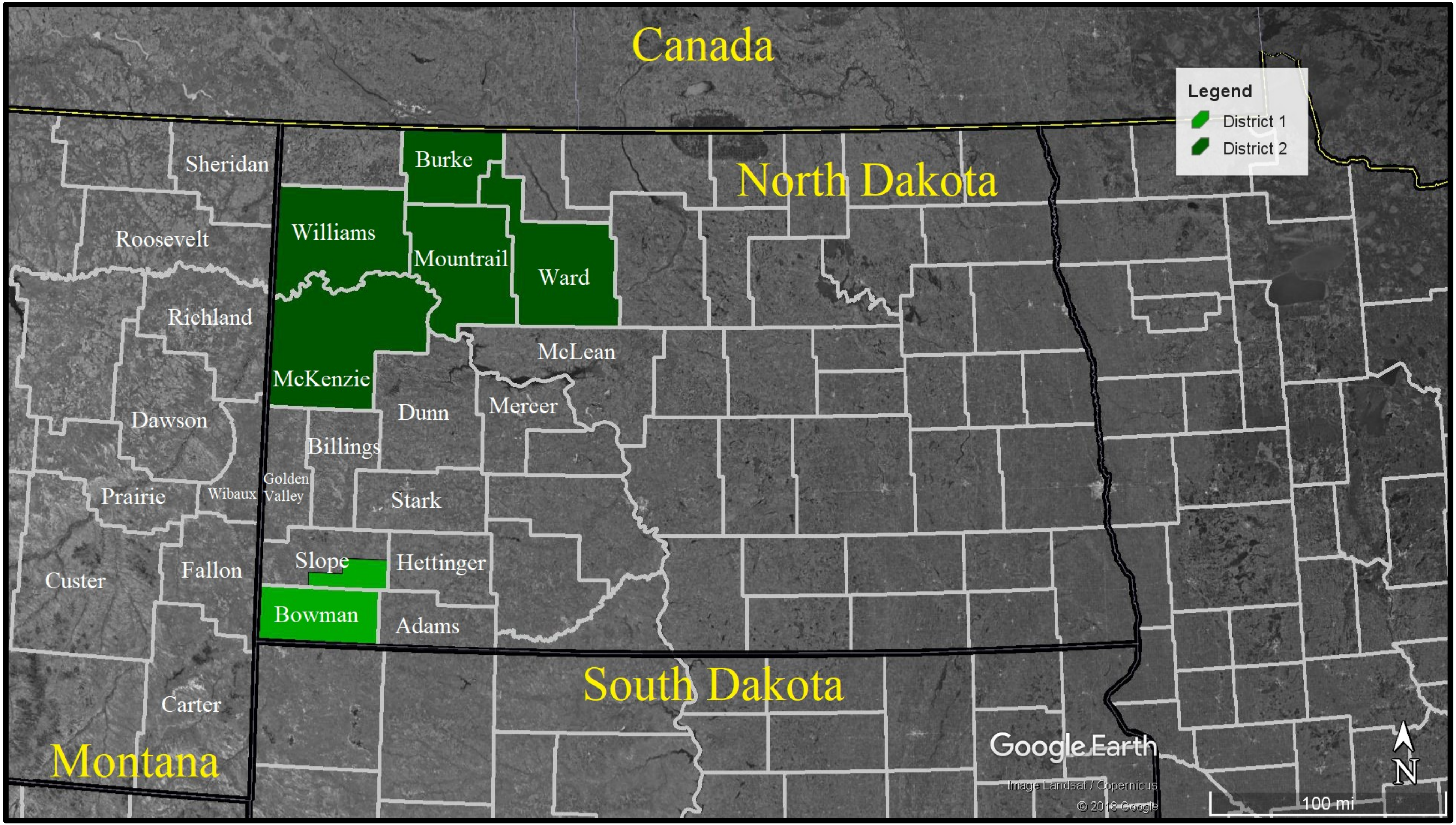
Black Box Experiments

*Green text discussed in previous presentation.

North Dakota Cloud Modification Project

- A non-randomized cloud seeding program operated since 1976. (Schneider and Langerud 2011)
- Primary goal of the program is hail suppression to reduce crop loss with precipitation enhancement as a second objective.
- Program operations are conducted in two districts during June, July, August and occasionally early September.

*Green text discussed in previous presentation.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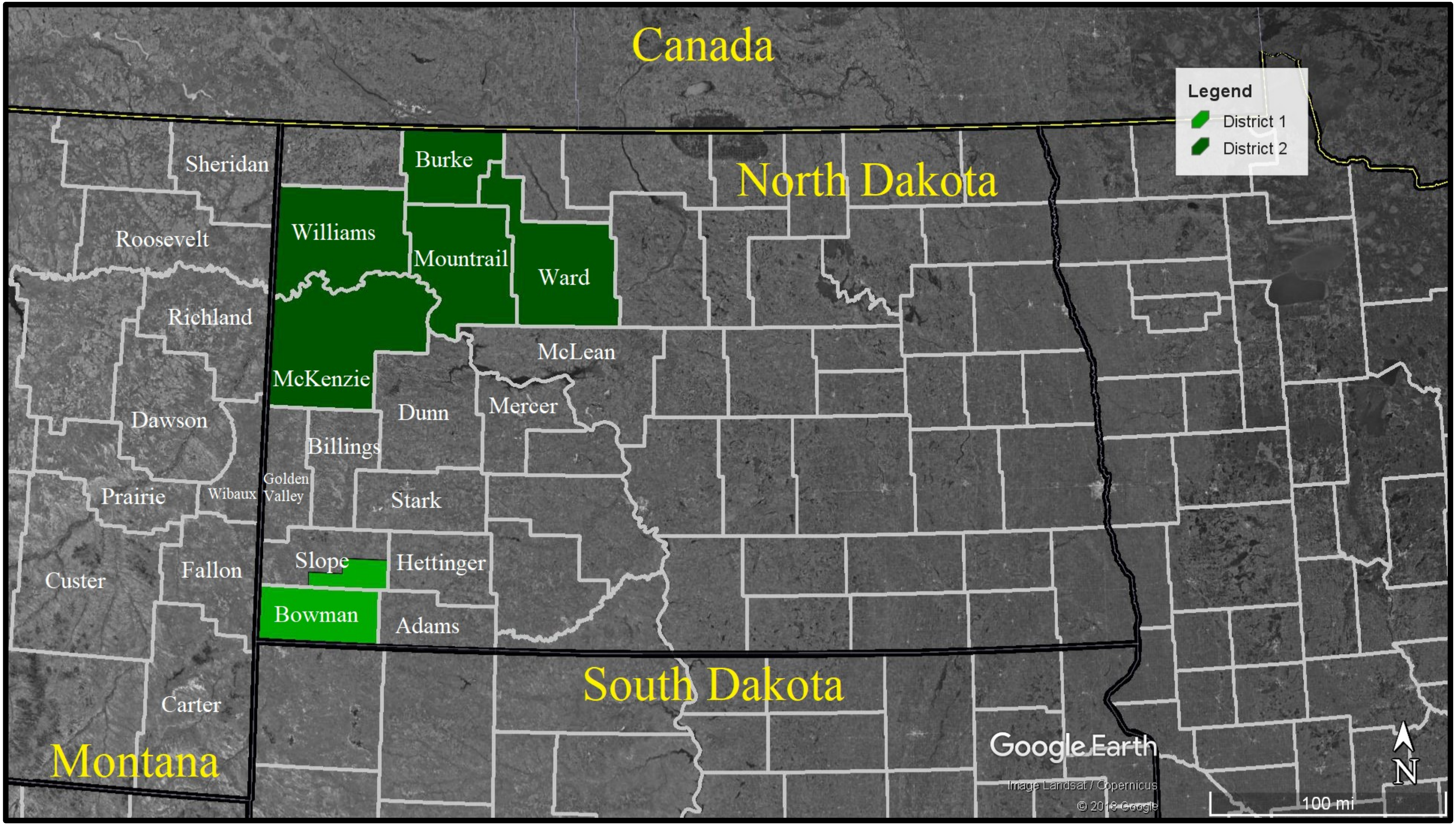
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Smith et al. 2004 Report

- Analyzed National Weather Service (NWS) Cooperative Observer Program (COOP) rain gauges to determine whether a cloud seeding effect was present.
- Used a target-control statistical analysis methodology that consisted of 11 target area stations and 25 control area stations located in eastern Montana.
- Results indicated little to no rainfall increase with a p-value (statistical significance level) of 0.32.

Wise 2005 Master Thesis

- Analyzed the project's effect using a target, downwind and control methodology.
  - The control/downwind region was determined by daily storm motion from 1999 to 2002.
- Analyzed 1977-2003 North Dakota Atmospheric Resource Board Cooperative Observer Network (NDARBCON) rain gauges data.
- Results indicated an increase in rainfall of at least 5 % in four out of seven cases.
  - Of those four, only two were determined statistically significant (p-value < 0.05).

Langerud and Gilstad 2003 Report

- Compared NDARBCON and NWS COOP gauges over a 23-year period from 1977-1999.
- Rain gauges were compared multi-annually and annually.
- Results indicated that rainfall totals are within approximately a half of an inch per year, with a correlation of 0.998.

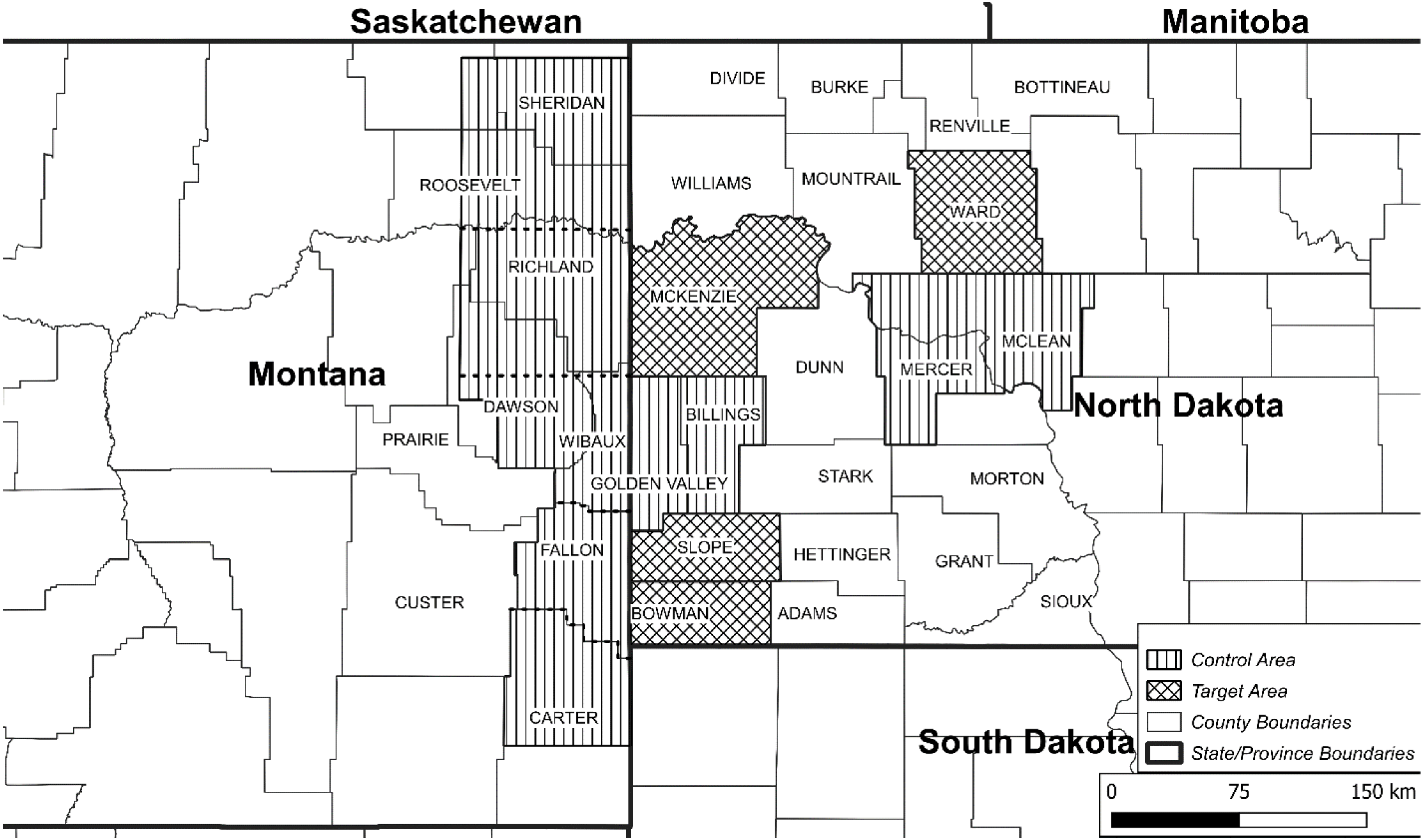
Tuftedal et al., 2022 Paper's Methodology

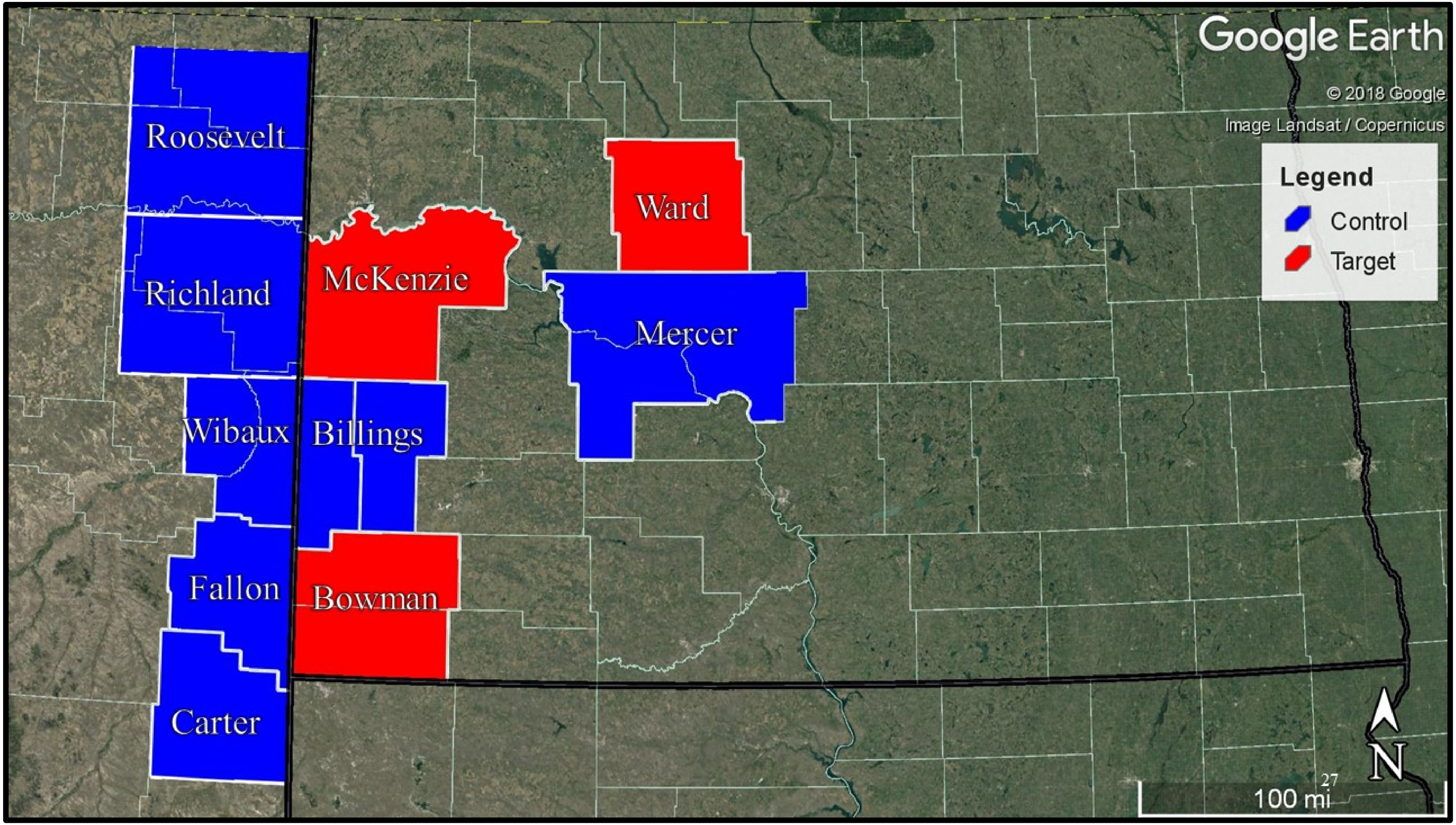
- Controls are designated as counties that have not participated in the North Dakota Cloud Modification Project, or only participated for relatively short period.
  - Downwind effects proved challenging for selecting controls.
  - DeFelice et al. (2014) found that downwind effects from cloud seeding increases rainfall by 5 – 15 %, and Wise (2005) found a 13 % increase in downwind rainfall.
- The target regions are determined by the years active in the North Dakota Cloud Modification Project.
  - Bowman, Slope, McKenzie, and Ward Counties are used.

North Dakota Cloud Modification Project Years Active in Conducting Operations

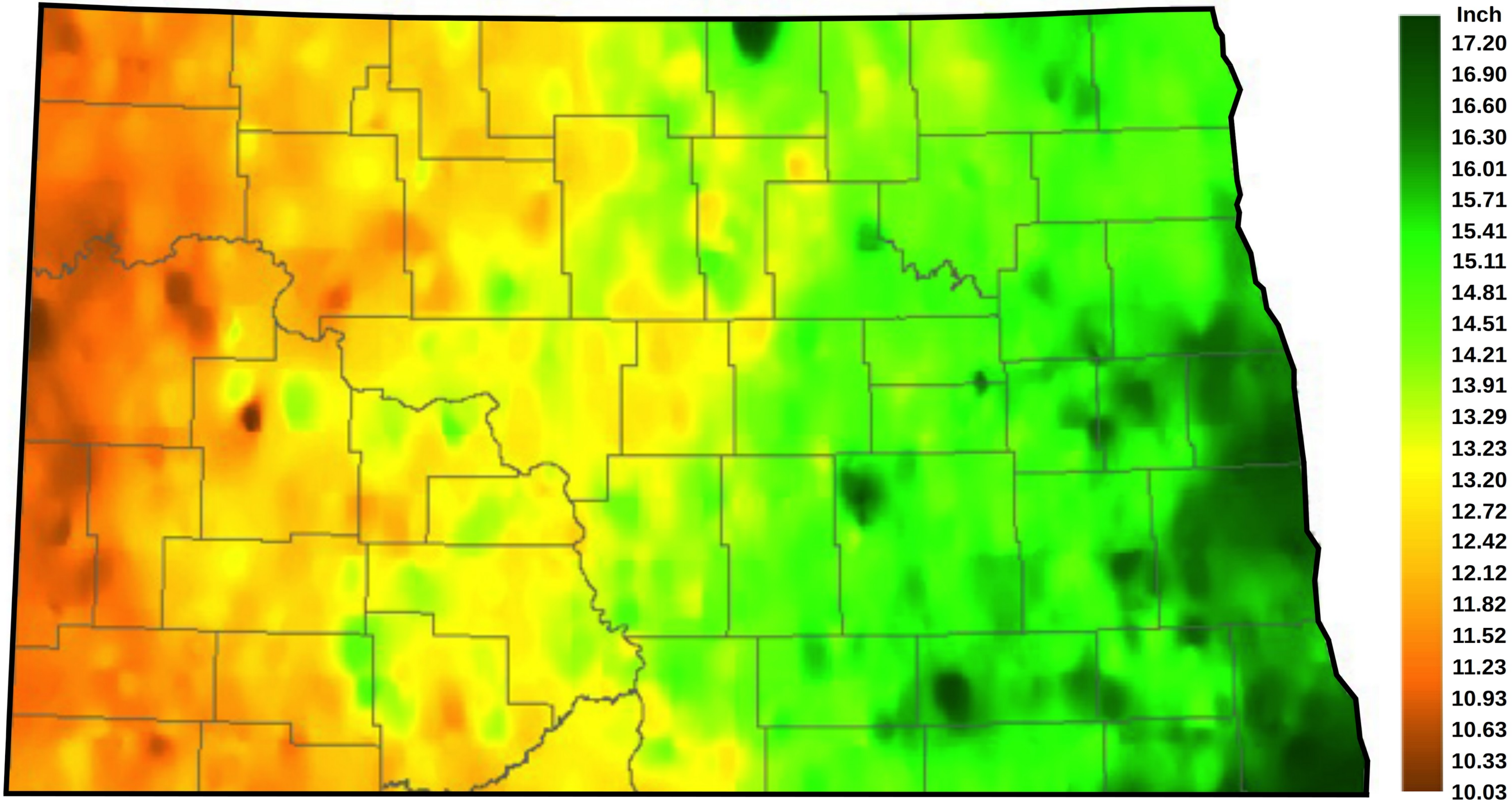
Counties	District	Years Participated	Total Years
Adams	1	1977-1980	4
Bowman	1	1977-2018	42
Hettinger	1	1977-1988	12
Slope	1	1977-2018	42
Burke	2	2015-2018	4
McKenzie	2	1977-2018	42
McLean	2	1977-1984	8
Mountrail	2	1977-2018	42
Ward	2	1977-2018	42
Williams	2	1997-2018	22

Target (crossed) and Control (vertical) Areas




Google Earth
© 2018 Google
Image Landsat / Copernicus
Legend
Control
Target
Roosevelt
Richland
Wibaux
Fallon
Carter
McKenzie
Billings
Bowman
Ward
Mercer
N
100 mi

30-year (1977-2006) Average Precipitation



Monthly Rainfall for a Single Station

$$M_s = \sum_{d=1}^{N} Rain_d$$

M_s is the calculated monthly rainfall for a given station (s).

Rain is the rainfall amount recorded on a given day (d).

N is the number of days in the given month.

Area Averaged Monthly Rainfall

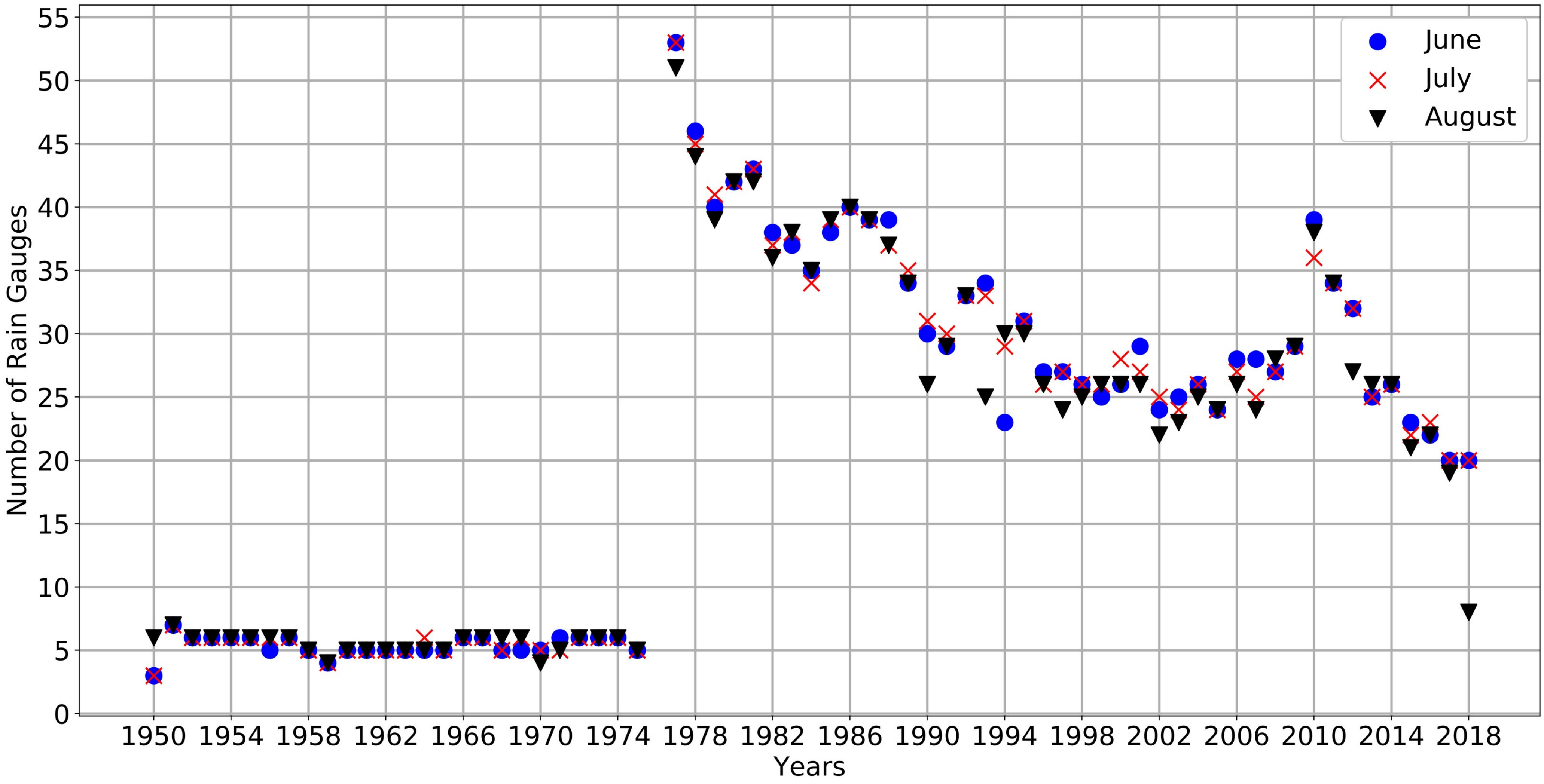
$$\overline{T_{area}} = \frac{\sum_{S=1}^{n} M_s}{n}$$

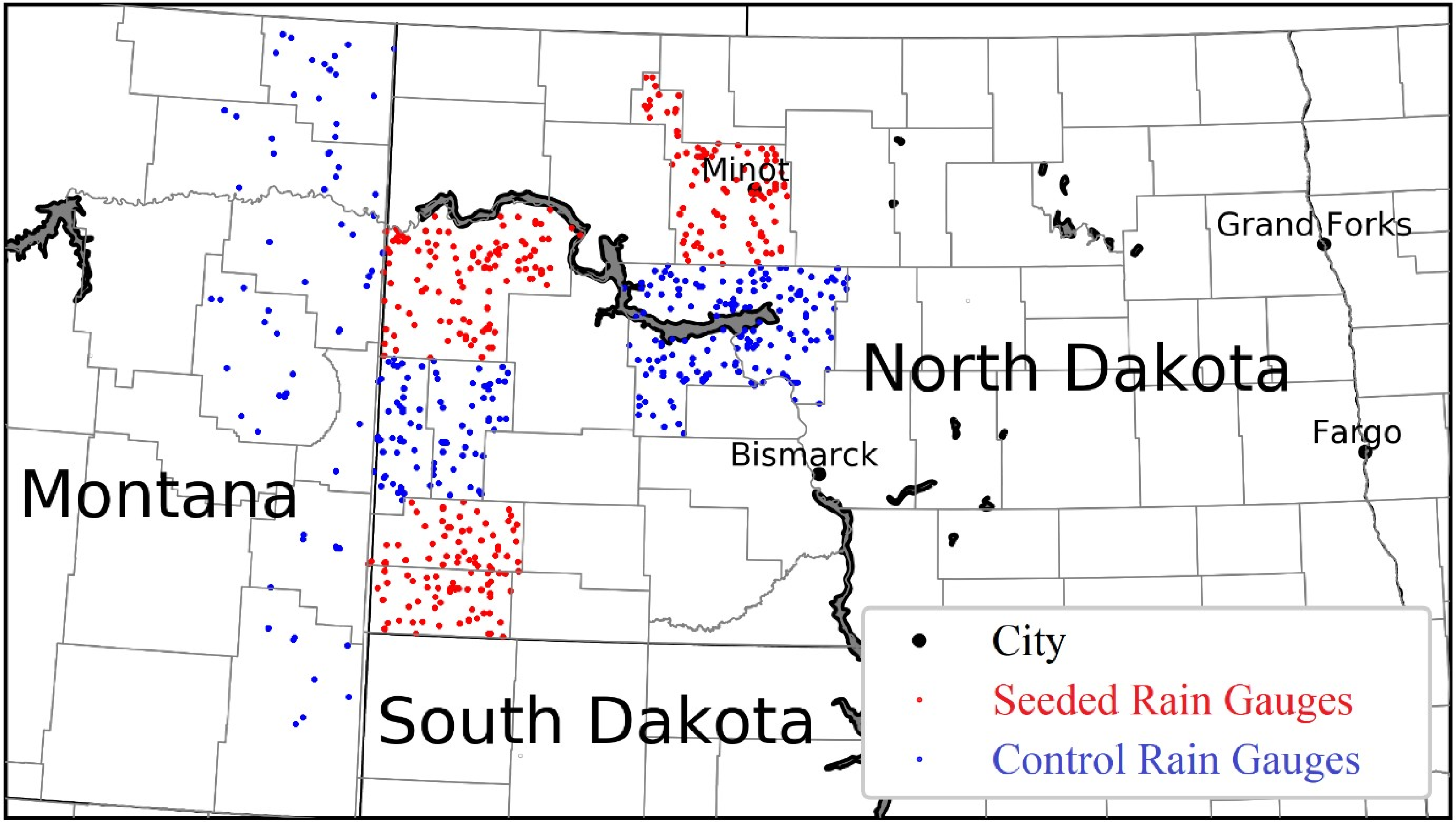
$\overline{T}_{area}$ is the average rainfall.

M_s is the calculated monthly rainfall for a given station (s).

n is the number of valid stations within the area.

McKenzie Counter Rain Gauge Stations (s)




Minot
Grand Forks
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Fargo
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City
Seeded Rain Gauges
Control Rain Gauges

Statistical Analysis Parameters Utilized

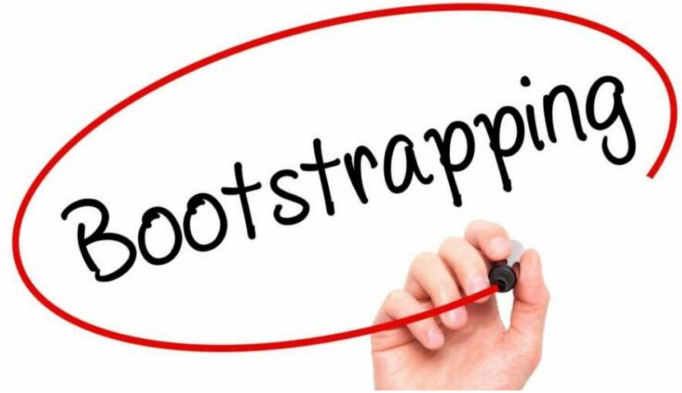
- Single Ratio

$$\frac{\square}{\square}$$

- Double Ratio

$$\frac{\square}{\square} / \frac{\square}{\square}$$

- Bootstrapping



Single Ratio (SR) Parameter

$$\frac{Target}{Control}$$

- Each target has a different control areas based on proximity.
  - McKenzie is paired with

    Richland, Roosevelt, Wibaux, and Billings.
  - Bowman is paired with

    Carter, Fallon, Wibaux and Billings.
- The single ratio for target and control areas are calculated using pre-NDCMP (1950-1975) and NDCMP (1977-2018) periods.

Area-wide Precipitation Using Rain Gauges

County	June (cm)		July (cm)		August (cm)		Seasonal (cm)	
	1950-1975	1977-2018	1950-1975	1977-2018	1950-1975	1977-2018	1950-1975	1977-2018
McKenzie	8.71	7.52	5.22	6.07	4.31	4.04	18.25	17.63
Bowman	9.26	7.60	5.28	5.27	3.94	4.00	18.48	16.88
Ward	8.82	8.66	5.70	6.50	5.09	4.73	19.61	19.90
Billings	10.29	7.52	5.47	5.90	4.66	4.50	20.42	17.92
Mercer	8.87	8.87	5.95	6.96	4.86	5.08	19.68	20.62
Wibaux	9.87	7.17	5.30	5.57	4.47	4.29	19.64	17.03
Richland	7.70	6.38	4.90	5.40	4.12	3.43	16.72	15.22
Roosevelt	7.17	6.66	4.79	5.69	4.23	3.37	16.19	15.72
Carter	9.78	8.32	5.52	5.45	3.88	4.54	19.18	18.31
Fallon	7.67	6.34	4.37	4.10	3.14	3.25	15.18	13.69

Single Ratio (SR) Equation

$$SR = \frac{\sum_{n=1}^{years} \overline{T_{target}^{\text{June, July, August, or Seasonal}}}}{\sum_{n=1}^{years} \overline{T_{control}^{\text{June, July, August, or Seasonal}}}}$$

$\overline{\mathrm{T}}$ is the average rainfall in an area (target or control) for a period (June, July, August or Seasonal).

Target/control Area-wide Single Ratios

Target/Control	June (cm)		July (cm)		August (cm)		Seasonal (cm)	
	1950-1975	1977-2018	1950-1975	1977-2018	1950-1975	1977-2018	1950-1975	1977-2018
McKenzie/Billings	0.84	1.00	0.95	1.03	0.92	0.89	0.89	0.98
McKenzie/Richland	1.13	1.17	1.06	1.12	1.04	1.17	1.09	1.15
McKenzie/Wibaux	0.88	1.05	0.98	1.09	0.96	0.94	0.92	1.03
McKenzie/Roosevelt	1.21	1.12	1.09	1.06	1.02	1.20	1.12	1.12
Bowman/Billings	0.89	1.01	0.96	0.89	0.84	0.88	0.90	0.94
Bowman/Wibaux	0.93	1.06	0.99	0.94	0.88	0.93	0.94	0.99
Bowman/Carter	0.94	0.91	0.95	0.96	1.01	0.88	0.96	0.92
Bowman/Fallon	1.20	1.19	1.20	1.28	1.25	1.23	1.21	1.23
Ward/Mercer	0.99	1.01	0.96	0.93	1.04	0.93	0.99	0.96

Double Ratio (DR) Equation

$$DR = \frac{SR_{1977-2018}}{SR_{1950-1975}}$$

SR is the average rainfall in an area (target or control) for a period (June, July, August or Seasonal) over many years.

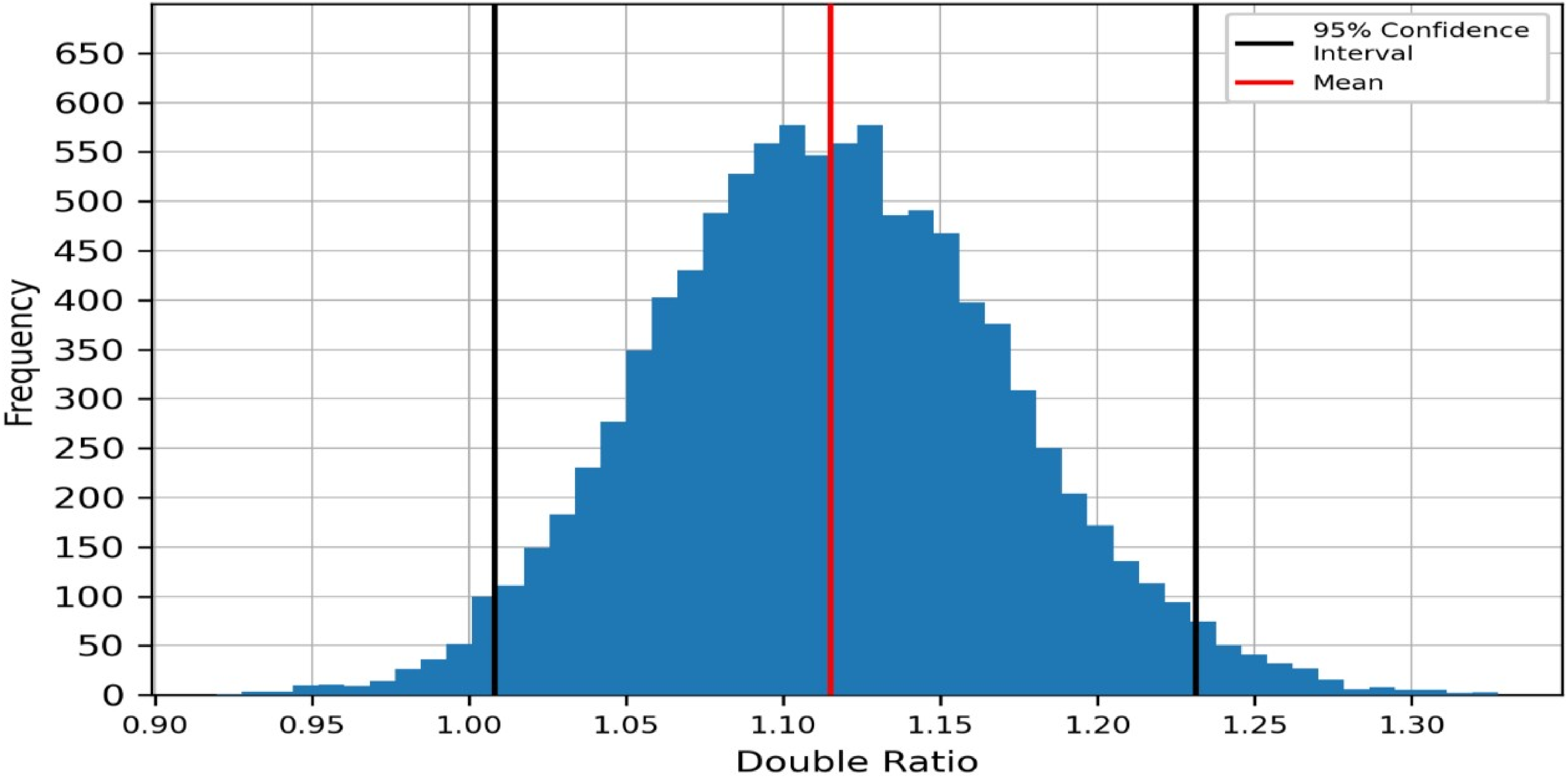
Target/control Area-wide Double Ratios

Target/Control	June (cm)		July (cm)		August (cm)		Seasonal (cm)	
McKenzie/Billings	1.19	1.08	0.97	1.10	0.92	0.89	0.89	0.98
McKenzie/Richland	1.04	1.06	1.13	1.06	1.04	1.17	1.09	1.15
McKenzie/Wibaux	1.19	1.24	0.96	1.12	0.96	0.94	0.92	1.03
McKenzie/Roosevelt	0.93	0.97	1.18	1.00	1.02	1.20	1.12	1.12
Bowman/Billings	1.13	0.93	1.05	1.04	0.84	0.88	0.90	0.94
Bowman/Wibaux	1.14	0.95	1.06	1.05	0.88	0.93	0.94	0.99
Bowman/Carter	0.97	1.01	0.87	0.95	1.01	0.88	0.96	0.92
Bowman/Fallon	0.99	1.07	0.98	1.01	1.25	1.23	1.21	1.23
Ward/Mercer	1.02	0.97	0.89	0.97	1.04	0.93	0.99	0.96

Bootstrapping Statistical Analysis Method

- Bootstrapping is used to randomly re-sample the data set multiple times to enable calculation of uncertainty, confidence intervals, and significance (Hesterberg et al. 2005).
- Bootstrapping does not assume a Gaussian, or any specific statistical distribution, for the data set population
- One-tailed statistical test is used to determine whether the double ratio for a particular target/control pair is statistically significant.
- A one-tailed statistical test checks if the critical area of a distribution is greater than or less than a specified value (Lane et al. 2003).

Distribution of Double Ratios from Area-wide, Seasonal Precipitation Averages for McKenzie/Wibaux



Target/control Area-wide Double Ratios

Target/Control Pair	DR	95% Confidence	Significance > 1.0	U-test	p-value
McKenzie/Billings	1.10	0.99 - 1.22	96.5%	667.0	0.128
McKenzie/Richland	1.12	1.01 - 1.23	98.5%	720.0	0.029
McKenzie/Wibaux	1.06	0.98 - 1.15	94.0%	687.0	0.076
McKenzie/Roosevelt	1.00	0.90 - 1.10	46.5%	552.0	0.945
Bowman/Billings	1.04	0.93 - 1.16	75.0%	589.0	0.592
Bowman/Wibaux	1.05	0.94 - 1.17	85.0%	620.0	0.354
Bowman/Carter	1.01	0.91 - 1.12	60.0%	598.0	0.516
Bowman/Fallon	0.95	0.86 - 1.05	19.0%	561.0	0.855
Ward/Mercer	0.96	0.87 - 1.07	27.5%	512.0	0.672

Conclusions

- The summer season double ratios have six of the nine target/control pairs where targets receive at least 2%, or more, precipitation than expected based on the corresponding control area.
- Based on the one-tailed significance test, six of nine double ratios indicate precipitation increases with two being statistically significant at the 95% confidence level and three being statistically significant at the 90% confidence level.
- For all nine target/control pairs, the seasonal average ratio is 1.03

Items of Note

- Results are lower limit ratios due to contamination of the pre-project period data by some seeding activity and possible effects of seeding on control areas during the NDCMP period.
- Although changes in target/control correlations in natural precipitation between pre-NDCMP and NDCMP periods are small they contribute additional uncertainty in interpreting the double ratio results.
- Results indicate somewhat smaller precipitation increases than the earlier analysis (Wise, 2005), which used a subset of the period analyzed here and a completely different analysis approach.

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