Impacts of freshwater salinity levels on crop productivity in agricultural river basins in the United States

MSc Thesis

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Abstract

Freshwater salinisation is an increasing global concern as it is a major factor which contributes to reductions in crop yields. Investigating the impacts of salinisation on crop productivity and monitoring the current levels of salinity in agricultural basins is crucial to ensure the prevention of yield declines.

The Great-Plains is one of the most important agricultural regions in the United States and vital to the nation's economy. In recent years challenging environmental conditions in the Great Plains coupled with land-use change has increased the risk of salinisation and sodification and these patterns have been studied. Few studies have investigated exceedance salinity thresholds for different crop types and estimated loss of crops within the Great Plains of the United States. There can be great insight in synthesising surface water, groundwater and soil salinity data with crop data and conducting analysis on a watershed level. Therefore, the objective of this thesis is to investigate spatiotemporal trends in salinity levels, its relation to crop specific salinity threshold exceedances and potential crop losses in a selection of agricultural watersheds in North Dakota over the last two decades. The results of statistical tests such as Mann-Kendall and Wilcoxon-Sign tests show that surface water salinity tends to increase a considerable amount downstream, even at a watershed scale, and increased from 2001-2020. Furthermore, crop salinity threshold analysis shows that over the past decade, a greater number of crop salt tolerance thresholds have been surpassed. Synthesis of crop acreage data and crop salinity threshold data showed the maximum potential production of dry beans – a saline sensitive crop – is impacted by temporal trend of increasing salinity. This thesis also elaborates on salinity management measures utilised within the study region and possible solutions to the increase in salinity.

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1. Introduction

Salinisation of freshwater and soil is a global concern responsible for decreased crop yields in many regions worldwide (Alqasemi et al. 2021; Ivushkin et al. 2019; Negrão et al. 2017; Plaut et al. 2013). According to the Food and Agriculture Organization (FAO, 2008), more than 11 percent of irrigated areas globally is affected by salinity. Future projections further estimate that over 800 million hectares may be impacted by salinity over the coming decades (Parihar et al. 2015; Plaut et al. 2013). This is a main challenge for global food security, with a steadily increasing population that requires world agriculture to produce approximately 70% more food to meet the expected food demand for 9.1 billion people by 2050. (Zörb et al. 2019; Parihar et al. 2015).

Both natural and human-induced processes can generate saline conditions throughout a region. Salinity can be attributed to natural processes involving the weathering of parent rock material containing soluble salts, which causes a release of numerous ions to a soil solution (Schuler et al. 2019; Kaushal et al. 2018; Parihar et al. 2015; Plaut et al. 2013). There are also human-induced contributors such as the use of saline-rich water during irrigation schemes, accelerated weathering, fertilisers and road salts are key anthropogenic sources of soil salinity (Schuler et al. 2019; Kaushal et al. 2018; Plaut et al. 2013). Furthermore, irrigation water tends to add considerable quantities of salt that remains in the soil, becoming problematic as salt accumulates at the root zones if drainage is insufficient (Hassani et al. 2020; Kaushal et al. 2018; Parihar et al. 2015; Mass & Grattan, 1999).

Under saline conditions, inhibition of plant growth can occur. Salt stress can affect primary processes such as photosynthesis, protein synthesis, and transpiration due to excessive amounts of salt entering the plant creating an ion imbalance (Sabagh et al. 2020; Parihar et al. 2015). This can lead to an impediment of plant growth and a decline in final yield (Hussain et al. 2019). Saline sensitive crop types such as maize, rice, potatoes, flax, and beans all have low salinity tolerance levels ranging between 1000-1700µS/cm that begin to show an adverse response under saline conditions (Hussain et al. 2019; Plaut et al. 2013; Tanji, 2002; Mass et al. 1983). Furthermore, a reduction in yield occurs when salinity levels surpass tolerance levels which differ between crop types (Hussain et al. 2019; Mass, 1993). Once threshold levels are exceeded, the excessive amounts of Na^+ and Cl^- entering the plant tissues become toxic, causing a decline in yield and ultimately leading to plant demise if conditions persist (Hussain et al. 2019; Zörb et al. 2019 Tuteja, 2007).

Previous studies in the United States have made significant progress in understanding salinity trends throughout the country. For instance, a recent study by Kaushal et al. (2018) analysed 232 monitoring sites over the past 30 years, which showed positive trends in both salinity and alkalinity. Furthermore, the study created the concept of “freshwater salinisation syndrome” which has been used to better understand the intricate connections of hydrological flow path from varying watersheds and changes in water chemistry. One of the most prominent areas affected by salinisation syndrome found was the Midwestern United States (Kaushal et al. 2018).

The Great Plains Region is one of the most important agricultural areas in the United States. The region spans from Canada to Mexico and consists of two sub-regions: the Northern Plains and the Southern Plains (Bentrup et al. 2017) (see figure 1). More than 80% of land use in the Great Plains is for agricultural purposes which is vital for the nation's economy as it has a market value of approximately $92 billion (Shafer et al. 2014). Agricultural activities in the Northern Plains are dominated by cereal crop production of wheat, hay, corn, alfalfa, and soybeans, and other harvested crops, including barley, sugar beets, and sorghum (Bentrup et al. 2017; Parton et al. 2007). However, challenging environmental conditions in the Great Plains coupled with land-use change have increased the risk of salinisation and sodification (Kharel, 2016). These changes have resulted in billions of dollars of agricultural losses and endangering rural economies dependent on agricultural output (Bentrup et al. 2017).

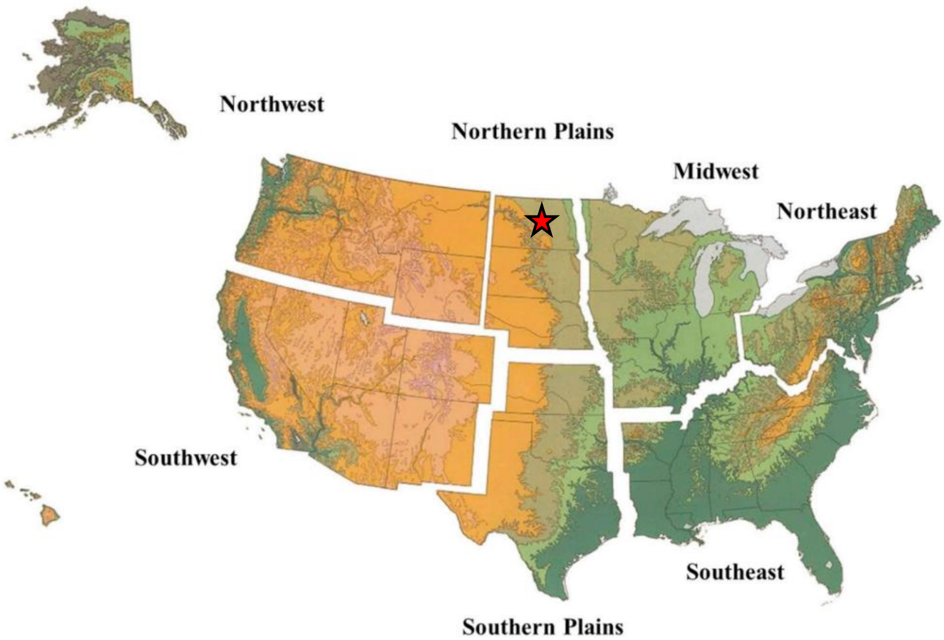


Figure 1: Map depicting the Great Plains (Northern Plains & Southern Plains) and the other five regions of the United States (Rotz et al. 2019). The star infers to the state of North Dakota, where the study sites are located.

North Dakota provides an ideal representative location of the Northern Great Plains since it is a region experiencing significant shifts in land use and increased soil salinity (Li & Merchant, 2013; Seelig, 2000). The state is the largest producer of wheat, barley, soybeans, and sunflowers in the United States due to its highly fertile soils (Li & Merchant, 2013). However, due to its mineral geology, most of the soil in the state has an electrical conductivity greater than zero (Franzen et al. 2019). This issue is further amplified by the high dissolved salt levels present in groundwater that mainly lies immediately below the water table (Franzen, 2003).

Although there are a number of studies that address the effects of salinisation on crops (Sabagh et al. 2020; Hadrich, 2012; Goff et al. 1998), few studies have investigated exceedance thresholds for different crop types and estimated loss of crops within the Great Plains of the United States. Additionally, there is little information analysing the correlation between historical salinity levels and annual crop yield within watersheds.

Objectives and Research Questions:

The objective of this thesis is to investigate spatiotemporal trends in salinity levels, its relation to crop specific salinity threshold exceedances and potential crop losses in a selection of agricultural watersheds over the last two decades. The research questions to be addressed are:

1. What are the spatial and temporal salinity levels in the investigated agricultural watersheds over the period 2001-2020?
2. To what extent are crop-specific salinity thresholds exceeded in the investigated crop areas of these basins?
3. Are there any correlations between historical salinity levels and crop land-use and/or yield changes in these regions?

To answer these questions, a data driven approach is taken to select agricultural watersheds in North Dakota with sufficient salinity data and crop acreage data such that statistical analysis can be performed. Spatial and temporal salinity trends are found by performing statistical tests outlined in section 2.3 and 2.5, and the results are interpreted and presented in sections 3.1-3.2 via mapping of data and figures. Trends in crop salinity threshold exceedances are investigated via boxplots and line graphs (see section 2.5), these are discussed in section 3.4-3.5. Lastly yield data, crop threshold and salinity data are synthesised following an approach discussed in section 2.7 to determine the potential crop yields in the watersheds. This was used to discuss correlations between historical salinity levels and crop performance in section 3.6.

2. Methods & Material

This study took a data driven approach in analysing salinity and crop data availability of North Dakotan agricultural watersheds. Data scouting and sorting of state-wide salinity monitoring datasets was streamlined by utilising data processing packages on Rstudio. As a result, two agricultural watersheds – the Middle Sheyenne and Forest watersheds - with sufficient salinity data and crop acreage data were selected for analysis over a period spanning 2001-2020. The spaciotemporal trend for both watersheds were conducted using visual and statistical analysis. State-specific crop tolerance salinity threshold information was then integrated with surface water, groundwater and soil electrical conductivity readings. Finally, state yield information was incorporated to evaluate the maximum potential production of each saline-sensitive crop under current conditions. This section will describe the sources and methods used to select the watersheds studied throughout this thesis, as well as introduce the methods used to analyse the salinity data within these watersheds.

2.1 Surface and groundwater salinity monitoring data collection and preparation

Data scouting and selection was performed using the USGS National Water Information System (NWIS) data portal, due to its vast inventory of water quality samples nationwide. Wider data exploration was conducted by obtaining additional surface and groundwater sites from the North Dakota Department of Water Resources and North Dakota Department of Environmental Quality. During this process, electrical conductivity (EC) data – the most common salinity indicator was queried using parameter code 00095 within the NWIS site selection criteria. The availability of EC data was then evaluated from the time period 2001 to 2020 for all surface water (SW) (rivers, streams and lakes) and groundwater (GW) monitoring stations in North Dakota.

The data processing stage utilised the software packages on Rstudio (data.table, dplyr, readxl, and lubridate) to sort the NWIS data and followed a similar site selection criterion to Thorslund & van Vliet (2020) (see figure 2). The R package allowed data to be sorted by monthly EC averages for surface water data and yearly averages for groundwater data. A lower observation criterion was applied to groundwater as subsurface monitoring resources have lower data availability and not as consistently available across the country (Dennehy et al. 2015; Reilly et al. 2008; IGRAC, 2020). For temporal analysis, the next step was to retain sites with at least 60 monthly observations for surface water and at least 15 annual observations for groundwater. Sites retained for further analysis from USGS and state government data are then projected on ArcGIS to evaluate the spatial distribution.

National 8-digit HUC data obtained from the USGS was added to assess which stations fall into particular watersheds. Stations were then spatially projected using Arcgis to evaluate the distribution of sites along the Great Plains and Corn Belt. This study focuses on North Dakota, and the Middle Sheyenne and Forest watersheds were selected for analysis. Both watersheds contained sufficient data satisfying the criteria in figure 2 and are situated within the Red River Valley (RRV), where land use is dominated by agriculture. Studying two different watersheds within North Dakota provides the potential to evaluate the difference crop types and management occurring in each area.

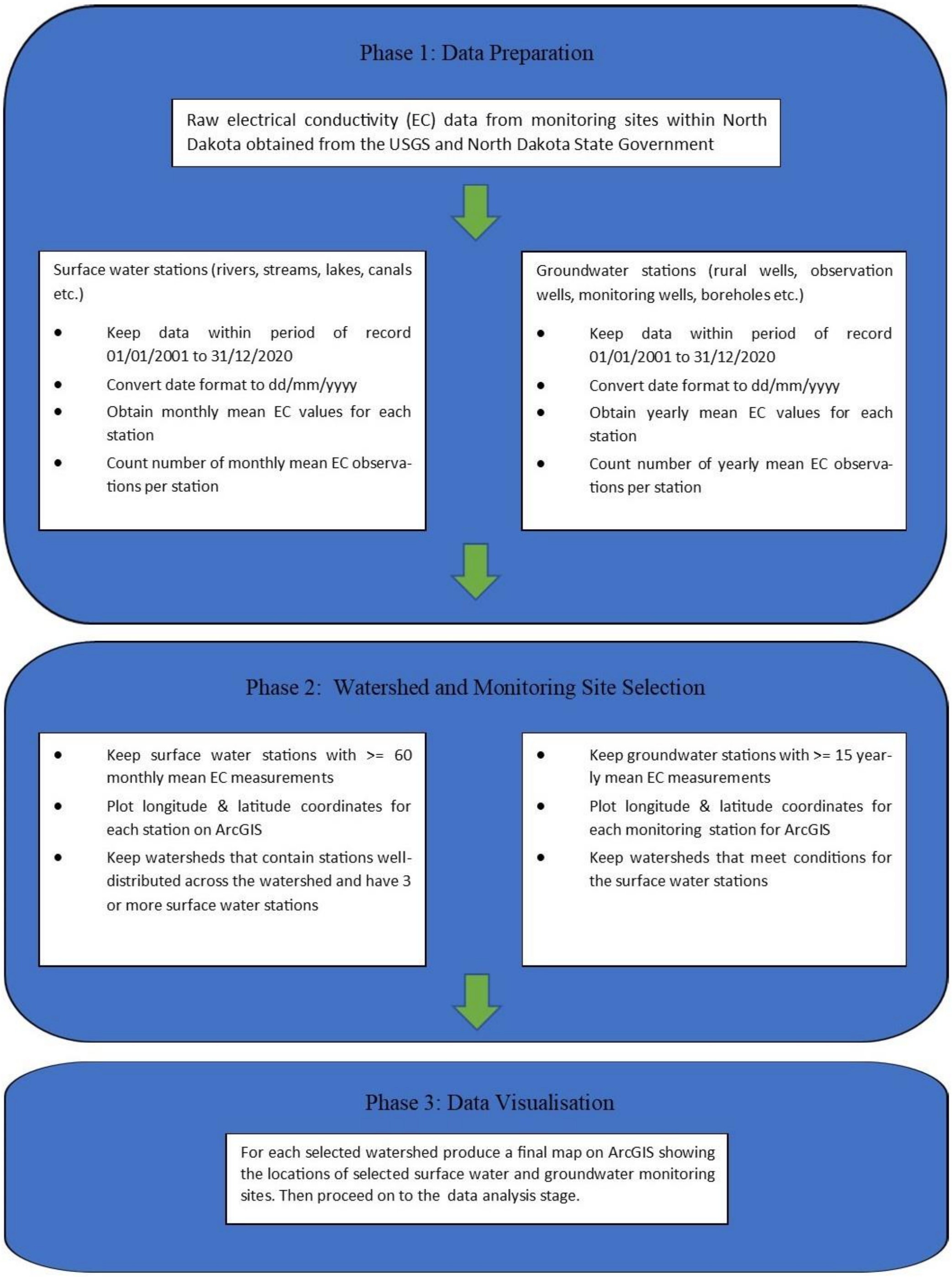


Figure 2: Site selection criterion for North Dakota sites (adapted from Thorslund & van Vliet (2020).

2.1.1 Site description

The Middle Sheyenne watershed (HUC09020203) covers approximately 1,283,384 acres (2,005 square miles) and is part of the Souris-Red-Rainy region of North Dakota (Hargiss, 2012) (see figure 3). The watershed is part of the Sheyenne River subbasin, one of the longest rivers in North Dakota and a tributary of the Red River (Macek-Rowland & Gross, 2010; Ryberg, 2007). Due to the Wisconsinan glacial retreat during the Late Pleistocene, the study area contains level topography and fertile soils, ideal for agriculture (Todhunter & Rundquist, 2008). According to the USDA National Agricultural Statistics Service (NASS) in 2020, the Middle Sheyenne watershed contains 59% of land use is agricultural, 21% grassland and pasture and 20% developed/other. In 2001 for Middle Sheyenne, 61% was agricultural, 25% was pastures/grassland and 14% (USDA, 2020; 2001). Soybeans, spring wheat, corn, dry beans, and alfalfa are the most commonly grown crops throughout the watershed.

The Forest watershed (HUC09020308) is the smaller of the two watersheds at 599,258 acres (740 square miles) and also part of the Souris-Red-Rainy region of North Dakota (Snoflow, 2022; Williams-Sether & Wiche, 1998). The Forest River is also a tributary for the Red River (Macek-Rowland & Gross, 2010; Shipunov et al. 2015). Land use in the Forest watershed is also a highly cropland dominated landscape (Arachchige & Perera, 2015). For the Forest watershed in 2020, 73% of land use is agricultural, 15% Grassland and pasture and 12% developed/other. In 2001 for Forest 83% is agricultural, 11% grassland/pasture, 6% developed/other. Spring wheat, soybeans, dry beans, corn, and sugar beets are among the most cultivated crops in the watershed according to the USDA NASS (2020; 2001).

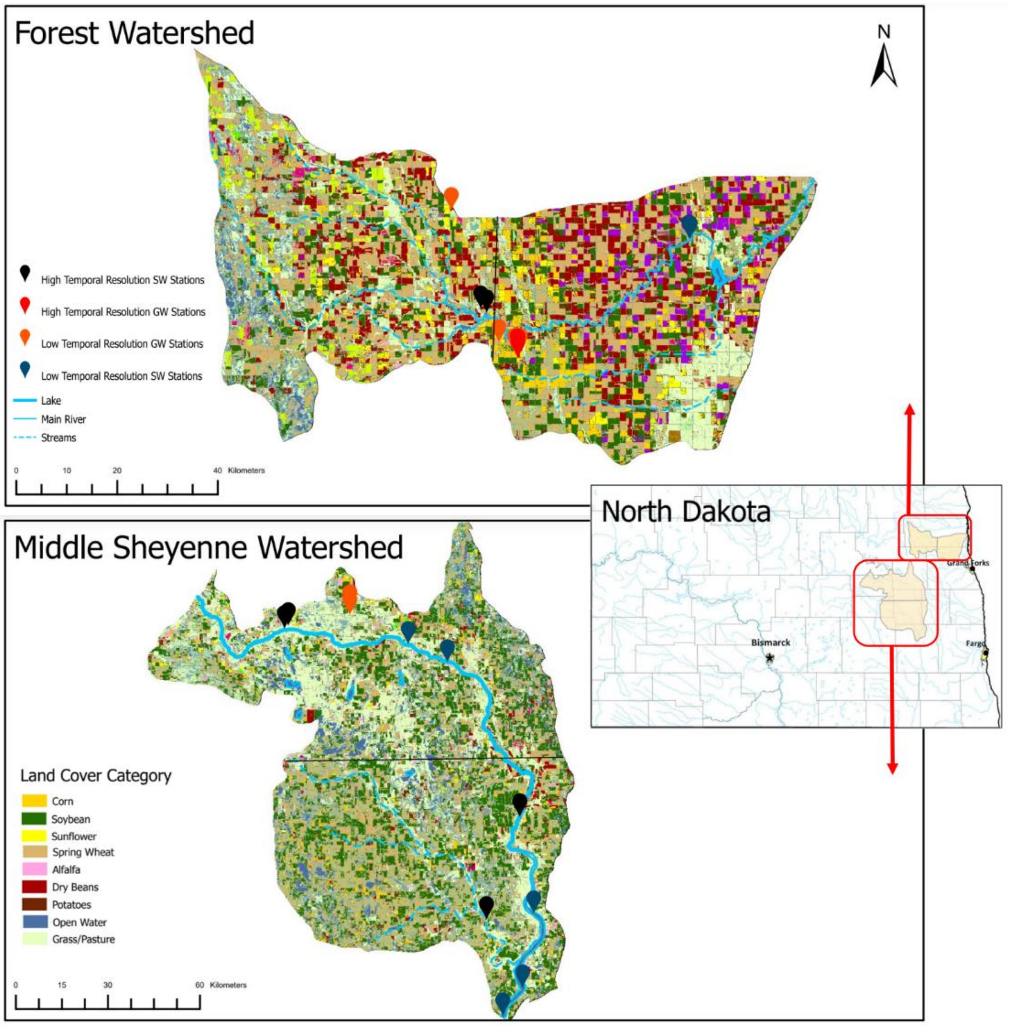


Figure 3: Study sites, the Middle Sheyenne watershed and Forest watershed with land cover categories of interest and spatial distribution of monitoring station types including the temporal resolution. High temporal resolution SW stations implies >=60 monthly observations. Low temporal resolution SW stations implies <60 monthly observations. High temporal resolution GW stations imply >=15 yearly observations and low temporal resolution for GW sites is <15 yearly observations.

2.2 Spatial sites evaluation

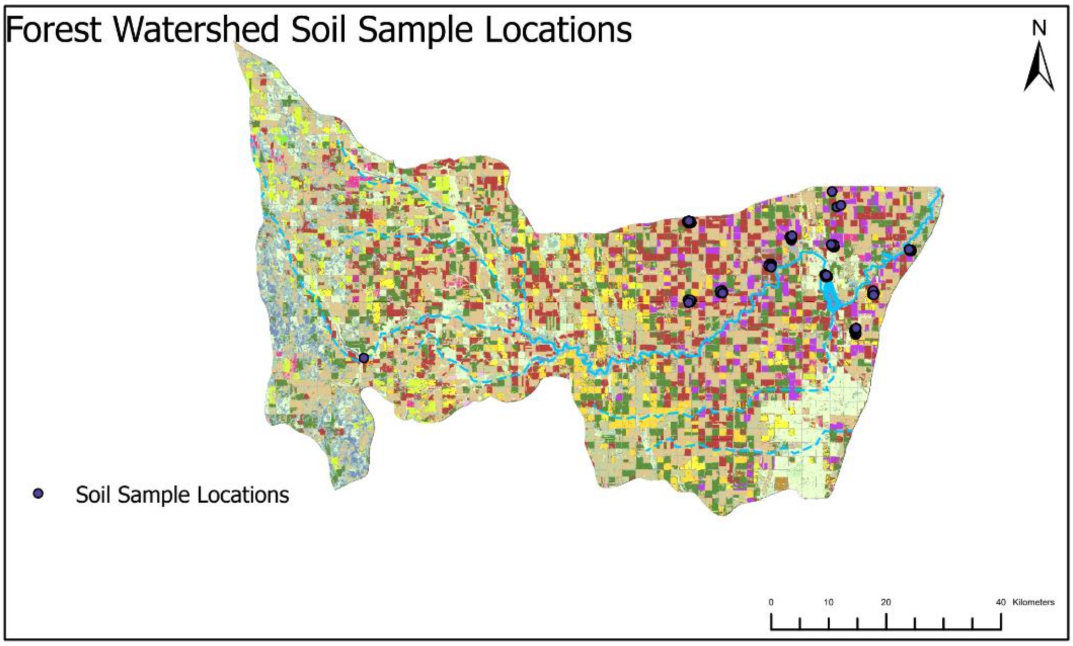
In order to fully evaluate the spatial distribution of salinity in both watersheds, additional surface and groundwater sites were analysed. These additional sites differ from the temporal sites selected using a criterion that aimed to obtain sites with the greatest temporal resolution; the spatial sites contain less observations, but provide an insight to the distribution of salinity throughout both watersheds. An additional seven surface water and three groundwater sites were added to the Middle Sheyenne watershed. For the Forest watershed, an additional two surface water and nine groundwater were added. Finally, all the stations were separated into upper and lower for Middle Sheyenne and left and right for Forest. This was done so the spatial trends of salinity can be investigated and splitting the watershed shows the heterogeneity of crop type acreages and salinity upstream and downstream.

2.3 Soil salinity data

Soil salinity data was obtained from the World Soil Information Service (WoSIS) in the form of spatial point data ArcGIS (WoSIS, 2022). This dataset measured electrical conductivity using the saturated paste method, a precise and widely accepted method of measuring electrical conductivity in the scientific community (Franzen, 2003). The dataset contained global soil salinity data with a sparse range of dates from 1970-2010, with some data points assigned no date label. With the Middle-Sheyenne and Forest watersheds there were only ~10 sites assigned date labels 2001-2020, and measurements were not frequent. Thus, due to the limited temporal and spatial nature of electrical conductivity soil samples, all available sample data for both watersheds were used and temporal salinity analysis was not conducted on soil salinity data (see figure 4).

The format of the soil salinity data contained profile information including site number, upper and lower depth of the soil profile (cm), electrical conductivity (dS/m) which was converted to microSiemens per centimeter (µS/cm) and date collected. Data contained electrical conductivity readings for three particular depths (e.g. 30-60cm, 60-90cm, 90-120cm etc.) and a range of other depths that required sorting into one of these three categories based on the average of the recorded depth range. These three depth intervals were analysed separately. Soil electrical conductivity samples were largely clustered (minimum distance between sites is 1km) to specific locations (see figure 4). Therefore, at each depth range, data in each cluster was aggregated (using Aggregate tool on ArcGIS with parameter: radius 1km) in order to obtain a good visual representation of the spatial distribution of salinity throughout both watersheds.

A



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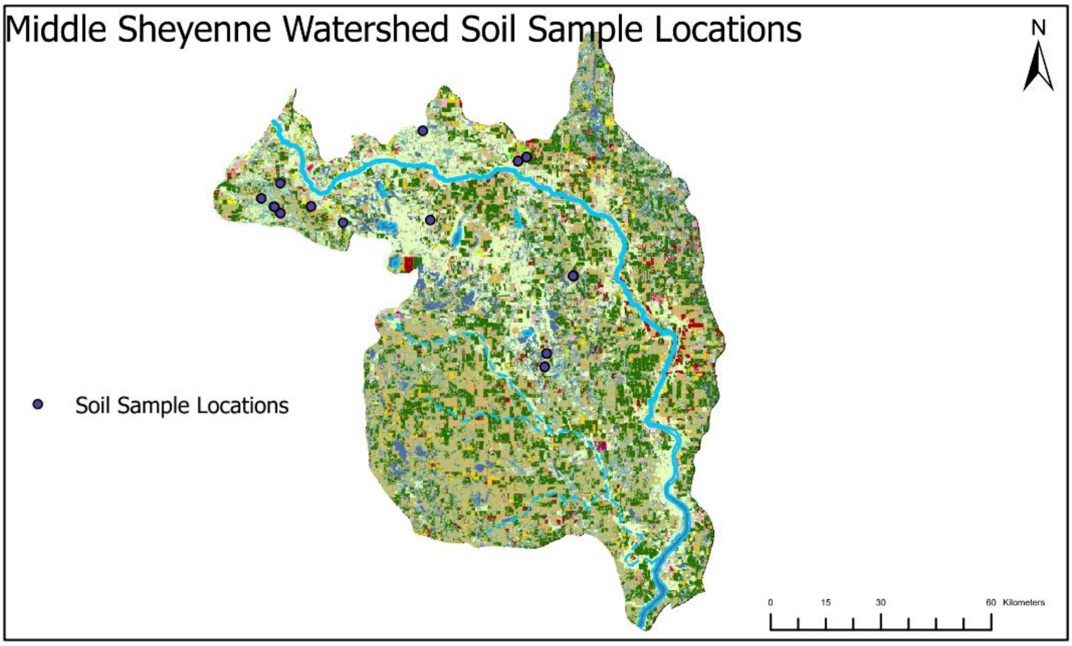


Figure 4: A) All the soil sample locations used for the Forest watershed. B) All the soil sample locations used for the Middle Sheyenne watershed (see tables A.2 & A.3 for coordinates of monitoring sites).

2.4 Crop salinity tolerance values

Annual crop acreage data for both watersheds from 2001 to 2020 were sorted to evaluate the crops with the most extensive acreage (see A.6). This then proceeded into the salinity threshold analysis stage. Crop salt tolerance threshold values collected by Franzen (2003), measured using the saturated paste method, provide tolerance ratings specific to North Dakota. Along with significant crops in the study site, saline sensitive crops found throughout both watersheds were included (see table 1).

Crop salinity threshold values and electrical conductivity data for all surface water and groundwater monitoring stations within both watersheds were then plotted on ggplot for 2001-2020. These time series plots provide a visual analysis of trends, potential seasonality and outliers of data which can be further investigated (Yu et al. 1993).

Table 1: Salinity tolerance threshold values for each crop type (Franzen, 2003).

Crop Type	Salinity Threshold (µS/cm)
Dry beans	1000
Potatoes	1500
Corn	1700
Alfalfa	2000
Sunflower	4800
Soybean	5000
Spring wheat	6000
Barley	8000

2.5 Statistical analysis

Statistical time series analysis is essential in order to understand and evaluate temporal trends in water quality (Sayemuzzaman et al. 2018). Preliminary analysis using a linear regression line of best fit can indicate a trend, but it doesn’t show if this trend is of statistical significance. Various studies and statistical methods exist for assessing changes and detecting trends in water quality (Fu & Wang, 2012). Therefore, selecting the most appropriate tests requires evaluation of factors such as the amount of data points, and distribution of the data. For this study electrical conductivity data was not normally distributed therefore, non-parametric tests were required (van Belle & Hughes, 1984).

Three different non-parametric tests were selected to detect linear water quality trends and evaluate the temporal changes between periods in time. They are: Mann-Kendall test, Sen’s Slope estimator, and the Wilcoxon-Sign test. These three non-parametric tests are widely used in water quality trend studies as they are all relatively robust and powerful methods (Meals et al. 2011). The Mann-Kendall test and the Sen’s Slope estimator are often used together as the former determines if there is a trend, and the later determines the magnitude of the trend (Mustapha, 2013). The Wilcoxon-Sign test is another well-established nonparametric test in water quality that assesses the difference between two sets of data.

2.5.1 Mann-Kendall test

The Mann-Kendall test is a well-known non-parametric test frequently used for monotonic trend analysis of a time series dataset (Kisi & Ay, 2014; Meals et al. 2011). This statistical test analyses the difference in signs between earlier and later data values (Khambhammettu, 2005). Assumptions that the tests use are that no serial correlation exists between variables and that the spread of distribution is constant (Helsel & Hirsch, 2002). Furthermore, data is not required to conform to a normal distribution (Meals et al. 2011). The Mann-Kendall statistic (S) is used to indicate whether or not the time series follows a trend as is defined by (Eq. 1).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(x_j - x_k\right), \tag{1}$$

Where the sign function is defined as,

$$sgn\left(x_j - x_k\right) = \begin{cases} 1 \; if \; x_j - x_k > 0 \\ 0 \; if \; x_j - x_k = 0 \\ -1 \; if \; x_j - x_k < 0 \end{cases} \tag{2}$$

Hence S will be positive, negative or zero. If S>0 there is a positive trend, S<0 indicates a negative trend. The test also returns a P-value. Since the test is conducted at a 95% confidence level, we accept there is a trend (determined by the sign of S) if P-value<0.05. Otherwise, we cannot conclude there is a significant trend.

Mann-Kendall tests were conducted for groundwater sites using the available yearly salinity data. Surface water data was available on a monthly scale, though there is a much higher number of measurements during period 2 (2011-2020) compared to period 1 (2001-2010). Therefore, two Mann-Kendall tests were conducted for surface water data: the first for monthly salinity data and the second for average yearly salinity data. The results of these tests are discussed in section 3.2 to determine if the skewed distribution of salinity data points in time influences the Tau and P-values.

2.5.2 Sen's Slope Estimator

The Sen's slope estimator is a non-parametric method that can be used to detect trends in water quality. This method is useful as it provides information regarding the magnitude of linear trend indicated by the Mann-Kendall test and is not greatly influenced by outliers (Yu et al. 1993). For this study, yearly electrical conductivity data for all surface water and groundwater sites were analysed to evaluate the annual rate of change in electrical conductivity trends. The method was developed by Sen (1968) and outputs the mean of the Sen's slope estimator which is a value indicating the magnitude of the gradient of a linear trend. To find it we first calculate the slope for each pair of salinity data points,

$$\mathrm{Q_i} = \frac{\mathrm{x_j - x_k}}{\mathrm{j - k}}, \tag{3}$$

Where $j > k$, so if we have n yearly salinity observations, we calculate $\frac{n(n-1)}{2}$ slopes. The Q_i's are then ranked in ascending order, and the median of the Sen's slope estimator (Q_{med}) is given by,

$$Q_{med} = \begin{cases} Q_{(N+1)/2} & if \ \frac{n(n-1)}{2} \ is \ odd, \\ \frac{1}{2}\left(Q_{N/2} + Q_{(N+2)/2}\right) & if \ \frac{n(n-1)}{2} \ is \ even. \end{cases} \tag{4}$$

If $Q_{med} > 0$ there is a positive trend, and if $Q_{med} < 0$ there is a negative trend. The larger the magnitude of Q_{med}, the stronger the trend.

2.5.3 Wilcoxon-Sign test

The Wilcoxon signed rank test is a non-parametric test that can be used to test if two groups of data statistically differ from one another. In this case we will use it to test if there is a significant difference in the median salinity data over two time periods. The test makes the following assumptions; variables are continuous, are independently sampled, and belong to one of two groups – period 1 (2001-2010) or period 2 (2011-2020) in the case. It makes no assumptions about sample following a normal distribution (Helsel & Hirsch, 2002). This is the non-parametric equivalent to the students t-test; histograms and quantile-quantile (QQ) plots (see A.3 and A.4) show the data is not normally distributed.

A paired test was conducted where yearly (average) data from each site was paired with the (average) yearly measurements from the same site 10 years later. For N sites with 10 paired-measurements this results in $N \times 10$ paired data points $(X_i, Y_i),\ i = 1, \dots, 10N$. This allows us to see if there is a difference in salinity readings over a ten-year period. We pair readings from each station in this way to avoid information loss and keep the number of data points high. If instead we took the average salinity reading from each site over period 1 and period 2 and paired these values, we would only have 6 paired data points for each watershed.

To conduct the test, we first compute the paired differences,

$$D_i = X_i - Y_i,\ i = 1, \dots, 10N. \tag{5}$$

These magnitudes of these differences are then ordered in ascending order and a rank R_i assigned to each,

$$R_i = rank(|D_i|), \tag{6}$$

Where $R_1 = 1 < R_2 < \cdots < R_{10N} = 10N$. The test statistic is then given by,

$$V = \sum_{i=1}^{10N} sgn(X_i) R_i, \tag{7}$$

R studio calculates the p value by comparing the test statistic, V, to the null distribution. We reject the null hypothesis, H_0 if $p \geq 0$ or $p \leq 0$ where we have chosen a 95% significance level. For both watersheds we have:

- H_0: There is no difference in measured electric conductivity over a period of 10 years.
- H_1: There is an increase in measured electric conductivity over a period of 10 years.

2.6 Salinity exceedance frequency

Analysing the salinity exceedance frequency is useful for observing the amount of electrical conductivity observations that are exceeding saline-sensitive crop thresholds in both watersheds. This was done by first computing the monthly mean electric conductivity for each site, and recording how many of these observations there are during period 1 (2001-2010) and period 2 (2010-2020). For each monitoring station, crop type and period, the number of data points exceeding the corresponding threshold value was recorded and divided by the number of noted observations for this site during the relevant time period (multiplied by 100) to find the percentage exceedance for each crop, site and period. The distribution of exceedance percentages for each crop could then be analysed by studying a boxplot.

Soil electrical conductivity data was then integrated with crop salinity threshold data in order to investigate exceedance percentages similar to the method in creating the exceedance boxplots. The effective rooting depth for each saline sensitive crop was used to find the required soil depth range (30-60cm, 60-90cm, 90-120cm) and electrical conductivity observation. This rooting depth was used as it is the depth of soil where a specific plant acquires the most water and nutrients (USDA, 1997). Consequently, high soil salinity levels at the effective rooting zone depth can hinder plant growth by decreasing water and nutrient uptake (USDA, 1997). Each crop has a specific effective rooting zone depth (see table 2) which was used to evaluate soil salinity conditions and exceedance in both watersheds. Other crops such as sunflower, soybean, spring wheat and barley were not incorporated within soil salinity analysis as they are mostly saline tolerant (Franzen, 2003).

Table 2: Effective rooting zone depths for saline sensitive crops from literature paired with available soil depths data from the WoSIS.

Crop Type	Effective Rooting Zone (Inches)	Effective Rooting Zone (cm)	Soil Zone from WoSIS (cm)	Rooting Zone Sources
Dry Beans	24	61	60-90	Osorno, 2013
Potatoes	18	46	30-60	USDA, 1997
Corn	24	60	60-90	USDA, 1997
Alfalfa	36	91	90-120	USDA, 1997

2.7 Acreage and yield data comparison

Synthesis of crop acreage data and crop salinity threshold data can be used to investigate the maximum potential production of crops for each watershed. Average electrical conductivity for each period was compared to the specific crop salinity tolerance thresholds. For each crop, data from Franzen (2003) provided the crop salinity tolerance thresholds and the percentage yield decrease for every 1dS/m exceeding the threshold salinity. Thus, in accordance with the method used in Franzen (2003) to generate table 6 in the paper, calculating this gives the percentage of the maximum yield expected at each site given the average EC reading. The percentage of maximum yield (% *max yield*) is calculated by,

$$\% \, max \, yield = \begin{cases} 100 & if \; EC_{av} < EC_{Thresh}, \\ 100 - \frac{EC_{av} - EC_{Th}}{\% \, yield \; decrease} & if \; EC_{av} > EC_{Thresh}. \end{cases} \tag{8}$$

Here, EC_{av} is the average electrical conductivity for each period, EC_{Th} is the specific crop salinity threshold, and the $\%\ yield\ decrease$ is the percentage yield decrease for every 1dS/m exceeding the threshold salinity. For each crop, the maximum production (kg) over the watershed is calculated by combining the crop acreage from Cropscape with the North Dakota yield per acre data from the USDA. Yield data is given in bushels/acre or cwt/acre so unit conversion to kg/acre was done (note this conversion is different for each crop type and was calculated using data from the USDA). Hence the maximum production over the watersheds (kg) is found by multiplying the specific crop acreage (kg) over the watershed with the yield,

$$Max. Production = CropAcreage \cdot Yield\left(\frac{kg}{acre}\right). \tag{9}$$

The maximum production for each crop and the percentage maximum yield can then be combined to find the potential production of each crop (kg) over the watershed, given the average salinity values that have been observed.

$$Potential \; production = Maximum \; production \cdot \frac{\% \max yield}{100}. \tag{10}$$

3. Results

The following section is separated into six parts to answer the research questions. First, the results of spatiotemporal trends of the Middle Sheyenne and Forest watersheds are discussed by analysing salinity trends over the 20 years. The following subsections present findings on acreage changes for dominant crop types over the last two decades, illustrated by line graphs and histograms that show shifts toward particular crop types. Analysis of specific crop salinity thresholds then integrates monitoring station salinity data to evaluate crop salinity exceedance levels throughout both watersheds. Finally, potential yield deductions of saline-sensitive crops in particular areas are investigated by evaluating exceedance values using a combination of salinity data from surface water, groundwater, and soil samples.

3.1 Spatial salinity trends

3.1.1 Middle Sheyenne

A spatial salinity trend exists between surface water stations along the Sheyenne River, where higher EC values are recorded downstream (see figures 5 & 6). Already at the upper half of the watershed, this trend is observable by the ~200µS/cm increase of electrical conductivity in surface water between the cluster of surface water monitoring stations at the top of the watershed and the two surface water monitoring stations downstream. On the other hand, there are no groundwater stations in the lower half of the watershed, so no conclusions can be made regarding spatial trends for groundwater.

Higher salinity values are observed within the lower half of the Middle Sheyenne watershed compared to the upper half during both time periods (see figures 5 & 6). The greatest electrical conductivity values of 1601-2000µS/cm occur at two SW monitoring stations situated on the lower half of the Sheyenne River which is the main river of the watershed. Salinity slightly lowers at the bottom of the watershed as the Sheyenne River, terminates into Lake Ashtabula. Electrical conductivity values range between 1400-1600µS/cm in the middle of the lake and 1201-1400 µS/cm at the south end of the lake. The two SW sites located on Baldhill Creek, a tributary to the Sheyenne River, have the lowest electrical conductivity readings within the whole watershed ranging between 827 to 1000µS/cm over the 20-year period. Overall, these values within the lower half of the Sheyenne River overall contain higher EC values compared to the upper half of the watershed.

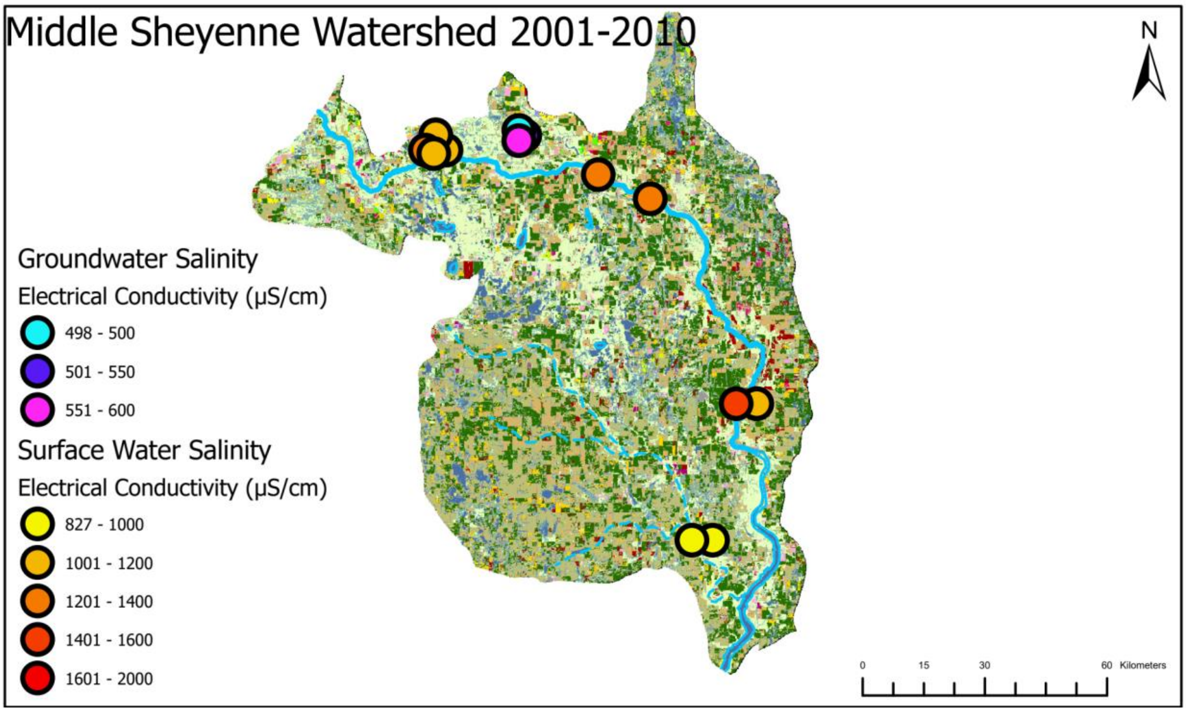


Figure 5: Surface water salinity and groundwater salinity averages for 2001-2010 for the Middle Sheyenne watershed. The average of the annual averaged salinity values at each monitoring station from 2001-2010 are displayed.

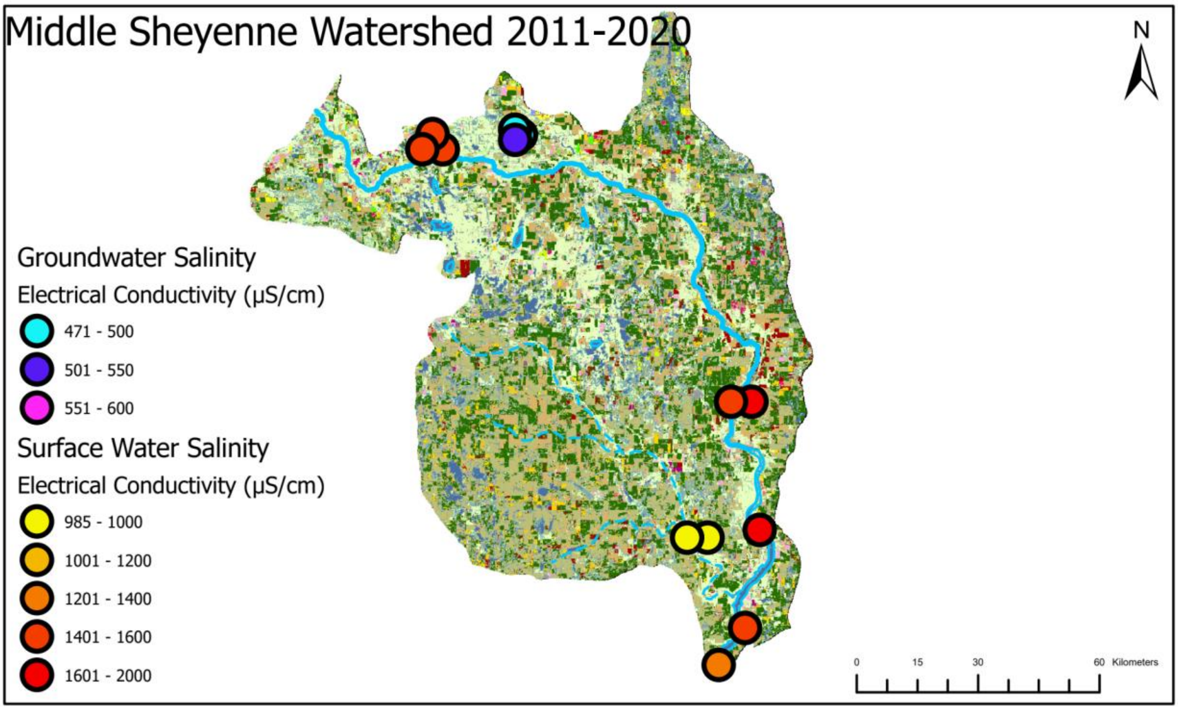


Figure 6: Surface water salinity and groundwater salinity averages for 2011-2020 for the Middle Sheyenne watershed. The average of the annual averaged salinity values at each monitoring station from 2011-2020 are displayed.

3.1.4 Forest watershed

The pattern of higher salinity values downstream is also present in surface water monitoring stations throughout the Forest watershed. Again, SW monitoring stations located upstream (Site ID 5084000 & 11090) have lower electrical conductivity values ranging between 882-1000µS/cm during periods 1 and between 1200-1400µS/cm during period 2 (see figures 7 & 8). Whereas SW monitoring stations downstream contain higher average salinity readings than the upstream monitoring stations during both analysed periods. Higher salinity values are observed at a cluster of surface water stations located at Minto on the far right of the watershed. EC values around this area range between 882-1200µS/cm during period 1 (see figure 7), which is higher than average EC observations upstream. This suggests that higher salinity values persist further along the Forest River, and salinity increases throughout the river course.

Groundwater monitoring sites, on the other hand, show a range of salinity values, and higher values do not follow the same increasing westward salinity trend that surface water follows. For example, groundwater site 13686 on the east side of the watershed has the highest EC values for periods 1 and 2 (see figures 7 & 8). Most groundwater sites are clustered on the right-hand side of the watershed near the village of Inkster, North Dakota. These groundwater wells show a similar range of values between 400-900 µS/cm.

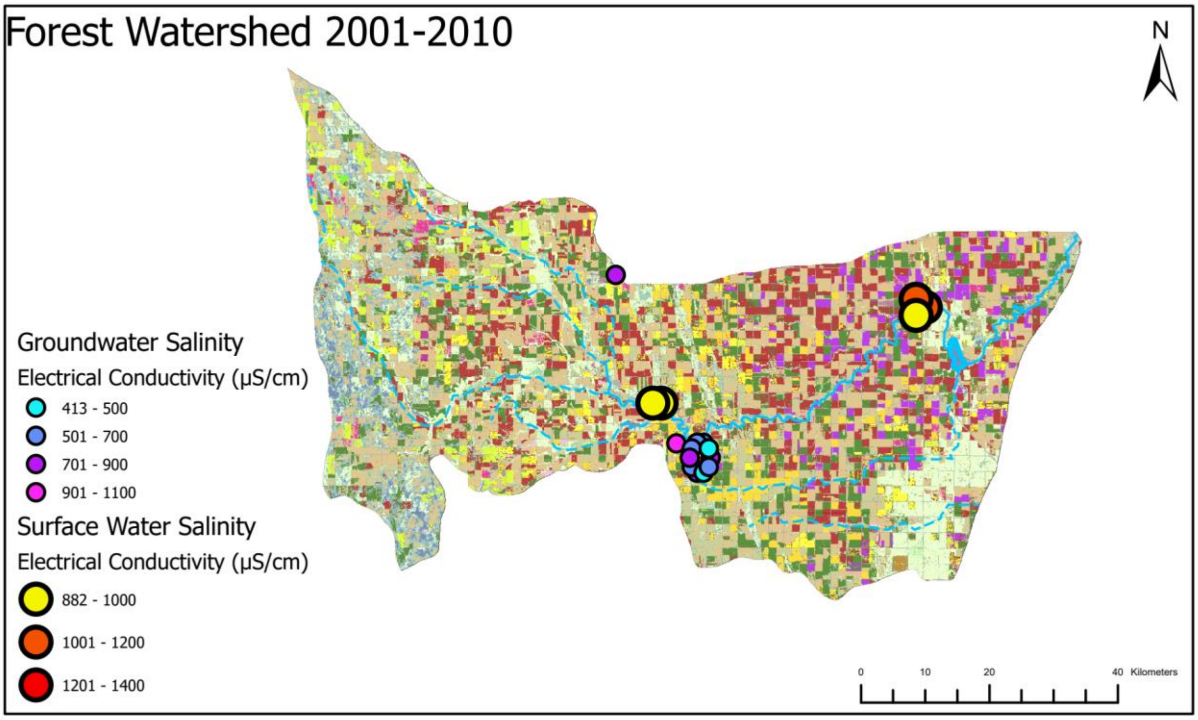


Figure 7: Surface water salinity and groundwater salinity averages for 2001-2010 for the Forest watershed. The average of the annual averaged salinity values at each monitoring station from 2001-2010 are displayed.

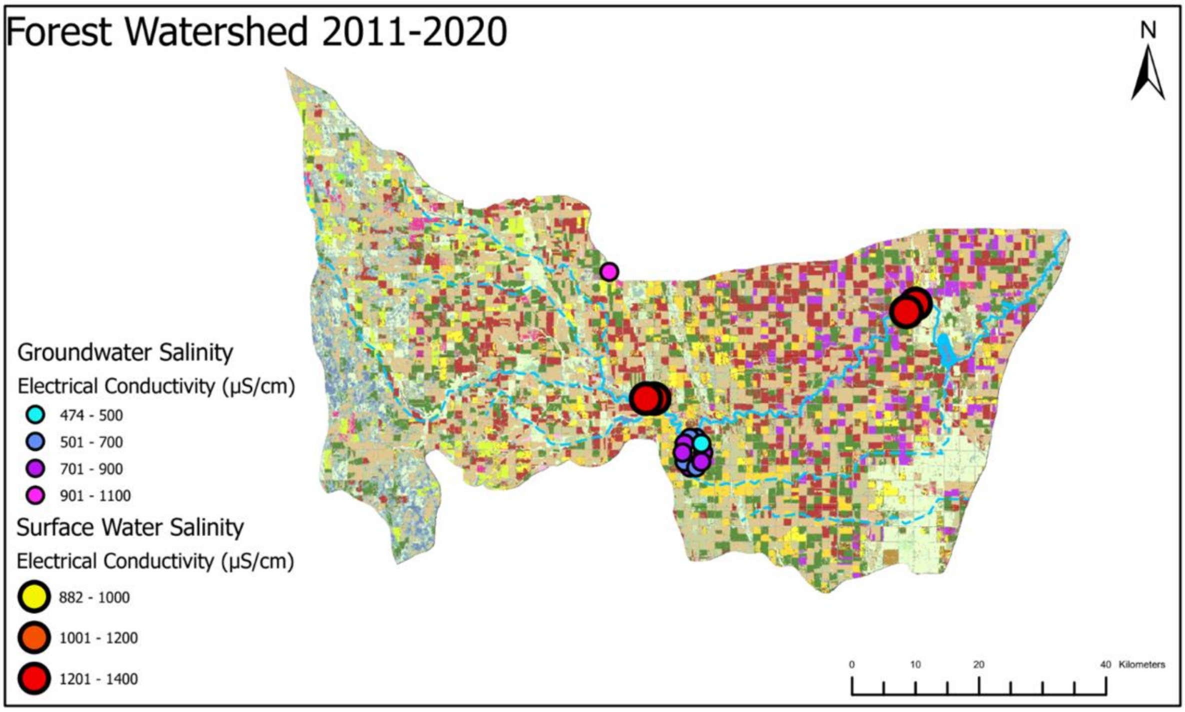


Figure 8: Surface water salinity and groundwater salinity averages for 2011-2020 for the Forest watershed. The average of the annual averaged salinity values at each monitoring station from 2011-2020 are displayed.

<u>3.2 Temporal salinity trends</u>

Electrical conductivity changes for the Middle Sheyenne and Forest watersheds display a collectively positive upward trend over the twenty-year period from 2001-2020 for all surface water and certain groundwater monitoring stations. Throughout the Middle Sheyenne watershed, all surface water monitoring stations show an increase in salinity (see figures 5 & 6). Surface water monitoring stations in the upper half of the watershed have all increased and show average annual salinity level increase by 200-400µS/cm. The salinity levels in the lower half of the Middle Sheyenne watershed have also increased and salinity levels also increase by 200-400µS/cm.

The same increasing surface water trend is seen in the Forest watershed (see figures 7 & 8). All surface water stations show salinity now ranging between 1201-1400µS/cm in 2011-2020 compared to 882-1200µS/cm from 2001-2010. During 2011-2020, there are slightly more groundwater sites in the forest watershed that record high salinity values in the range 701-900µS/cm compared to the previous decade.

Overall, there appears to be an increasing temporal trend in salinity, especially for surface water monitoring stations. Linear regression analysis using a line of best fit can further display these patterns for surface water and groundwater stations containing data points with high temporal resolution.

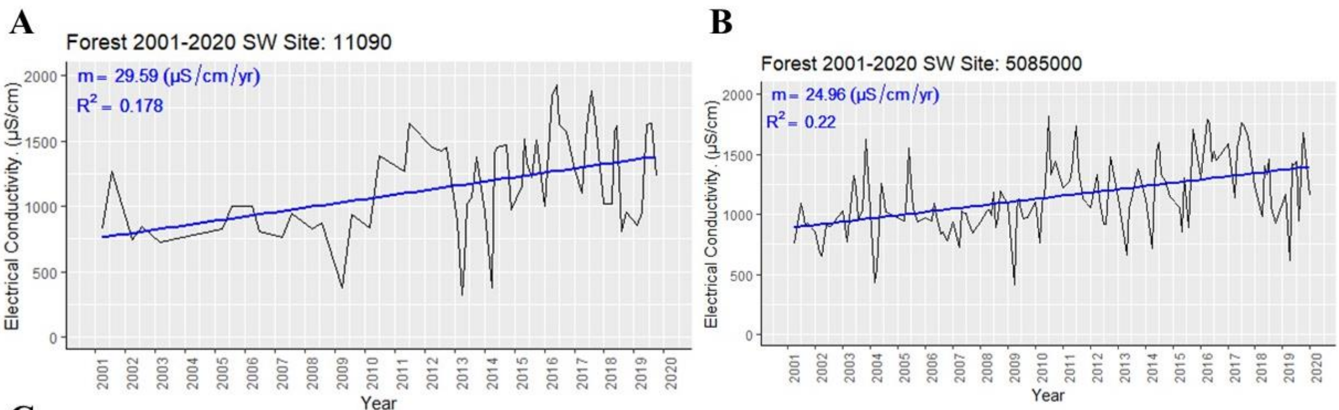
3.2.1 Linear regression analysis for electric conductivity rates

Linear regression analysis shows an increasing salinity trend recorded for all surface water and groundwater sites with high temporal resolution located in both the Middle-Sheyenne and Forest watersheds (figures 9, 10 and A.5).

All three surface water monitoring stations in the Forest watershed show a similar rate of electrical conductivity increase of 25-30µS/cm per year. Groundwater stations within the Forest watershed show a greater range of markedly lower yearly electrical conductivity rates compared to the surface water sites. Here the rate of change of electrical conductivity ranged from 4-16µS/cm per year. The Middle Sheyenne surface water monitoring sites show greater still variability in electrical conductivity rates compared to the Forest watershed. These rates range between 26-41µS/cm at sites located along the Sheyenne River, with higher rates observed downstream. Note that the tributary SW site 5057200 has a lower EC rate of 3µS/cm per year (see figure 10 & A.1).

The R^2 values, which measure the goodness of fit of the linear regression, should also be considered. If R^2 equals 1, the linear regression can be interpreted as fitting the data perfectly. As the value of R^2 decreases towards zero, this indicates that there is no linear relationship between salinity and time. Although the gradients on the lines of best fit (the EC rates) clearly indicate an increasing trend in salinity, the R^2 values mostly range from ~0.2-0.7. This indicates that the relationship between salinity and time may not be precisely linear. Hence, further statistical tests need to be executed to determine if the increasing trend indicated by the gradients of the lines of best fit is a significant trend.

Further analysis of the linear regression graphs (figures 9, 10 and A.5) reveals predominantly higher peaks of EC occurring during the latter decade. Therefore, readings were separated into two time periods (2001-2010 & 2011-2020) to analyse the temporal heterogeneity and evolution of salinity in both watersheds. Table 3 shows the average EC (µS/cm) for all sites in the 10-year periods and the percentage change. This indicates that there is an increase in salinity between 2001-2010 and 2011-2020 in both watersheds. Again, monitoring stations located downstream had the greatest increase in electrical conductivity for both watersheds. This is observable in table 3, where SW monitoring stations 380009 and 11090 contain a 39% and 43% increase in electrical conductivity (see A.1 for site location).



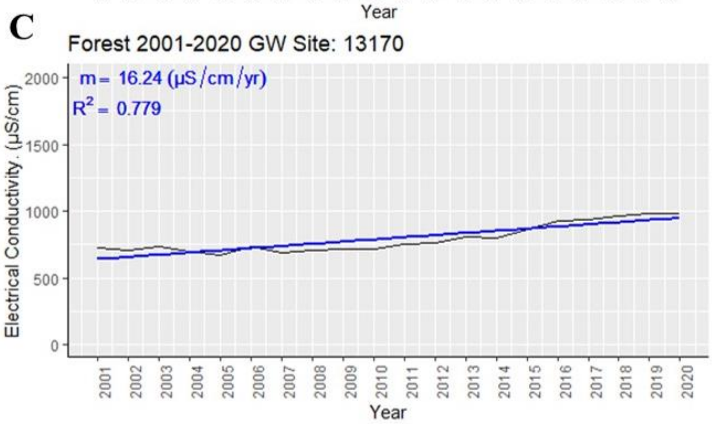
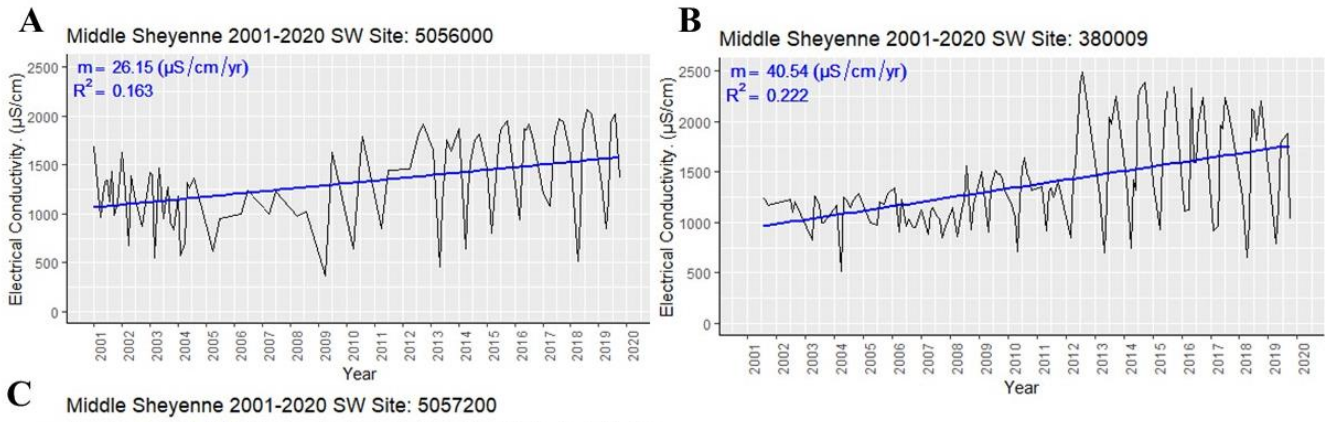


Figure 9: Selection of surface water and groundwater sites showing yearly averages with trend lines. M represents the slope or rate of increase of electrical conductivity (μS/cm) per year in each station. R^2 represents the goodness of fit of the regression model A) is SW station 11090. B) is SW station 5085000 and C) is groundwater well 13170.



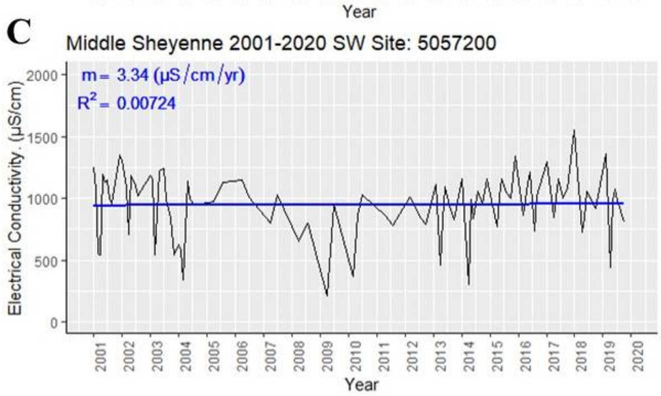


Figure 10: Selection of surface water and groundwater sites showing yearly averages with trend lines. M represents the slope or rate of increase of electrical conductivity (μS/cm) per year in each station. R^2 represents the goodness of fit of the regression model A) is SW station 5056000. B) is SW station 380009 and C) is SW station 5057200.

Table 3: Average electrical conductivity values (µS/cm) for each monitoring station for period 1 & 2 with the percentage change between period 1 and 2 for Forest and Middle Sheyenne.

Watershed	Site ID	Period 1	Period 2	Percentage Change (%)	Station Type
Middle Sheyenne	**5056000**	1128	1497	33	Surface water
Middle Sheyenne	**5057200**	928	985	6	Surface water
Middle Sheyenne	**380009**	1163	1616	39	Surface water
Middle Sheyenne	**24750**	1402	1432	2	Surface water
Middle Sheyenne	**5389**	1173	1465	25	Surface water
Middle Sheyenne	**3368**	827	986	19	Surface water
Forest	**5084000**	900	1255	39	Surface water
Forest	**5085000**	1013	1285	27	Surface water
Forest	**11090**	882	1263	43	Surface water
Forest	**13169**	740	845	14	Groundwater
Forest	**13170**	714	880	23	Groundwater
Forest	**19831**	643	685	7	Groundwater

3.2.2 Mann-Kendall tests for monotonic temporal salinity trends

Results from the Mann-Kendall test further confirm a significant increase and upward monotonic trend for nearly all sites for both watersheds. Table 4 shows a significant P-value with 95% certainty for almost all sites except SW site 5057200 in the Middle Sheyenne watershed. The Tau value is positive for all sites, thus, together with the P-value this indicates that there is a positive monotonic trend occurring for (almost) all sites. As discussed in section 2.5, average surface water data was recorded on both a yearly and monthly scale, and thus Mann-Kendall tests were conducted on both the yearly and monthly salinity data. Although these tests produce different Tau and p-values for all sites, the conclusions that they infer regarding significant monotonic trends is the same. It is interesting to observe that the P-values are always more significant for the monthly test (closer to zeros when we accept there is a trend (P-value<0.05) and larger otherwise).

Table 4: Mann-Kendall test results for surface water and groundwater sites with high temporal resolution in both watersheds. P-value, Tau and difference in Tau between yearly and monthly tests for the Middle Sheyenne and Forest watershed are shown. n.a. values for groundwater are present as there are not consistent monthly observations.

		Year		**Monthly**		
Watershed	**Site ID**	P-Value	Tau	P-Value	Tau	ΔT
Middle Sheyenne	**5056000**	0.00582	0.453	0.0002	0.262	0.191
Middle Sheyenne	**5057200**	0.16298	0.232	0.68541	0.0287	0.2033
Middle Sheyenne	**380009**	0.00388	0.474	3.58E-07	0.303	0.171
Middle Sheyenne	**24750**	0.04781	0.326	0.00032	0.194	0.132
Middle Sheyenne	**5389**	0.00036	0.602	2.37E-05	0.257	0.345
Middle Sheyenne	**3368**	0.02515	0.38	0.00763	0.223	0.157
Forest	**5084000**	0.00582	0.453	2.74E-06	0.335	0.118
Forest	**5085000**	0.00388	0.474	2.22E-16	0.35	0.124
Forest	**11090**	0.01177	0.427	0.00026	0.306	0.121
Forest	**13169**	0.00428	0.47	n.a	n.a	
Forest	**13170**	2.63E-05	0.712	n.a	n.a	
Forest	**19831**	0.11151	0.265	n.a	n.a	

3.2.3 Sen’s Slope test to detect magnitudes of trends

The calculated Sens’s slope estimators show a positive increasing trend for all sites in both watersheds (see table 5). The upstream surface water sites of the Middle Sheyenne watershed contain the greatest increasing rate of salinity (30-37µS/cm/yr) and these large increasing rates continue downstream to the other surface water sites (12-37µS/cm/yr). The two surface water sites located on Baldhill Creek also contain relatively high increasing rates (9-15µS/cm/yr).

Surface water sites in the Forest watershed follow the same trend with salinity rates in the range 21-29µS/cm/yr with the highest increasing annual rate observed upstream (site 11090) and the lowest downstream (site 5085000) (see A.1 for locations). Groundwater sites in the Forest watershed show more variable annual rates of salinity ranging from 4-16µS/cm/yr. The groundwater sites are clustered downstream so a spatial trend cannot be evaluated.

Table 5: Sen's Slope Estimator results for all high temporal resolution sites depicting the increasing yearly rate of electrical conductivity (µS/cm/yr) for the Middle Sheyenne and Forest watersheds

Watershed	Site ID	P-Value	Sen's Slope (µS/cm/yr)	Type
Middle Sheyenne	**5056000**	0.00582	29.79	SW
Middle Sheyenne	**5057200**	0.163	9.17	SW
Middle Sheyenne	**380009**	0.003883	11.53	SW
Middle Sheyenne	**3368**	0.02515	15.15	SW
Middle Sheyenne	**5389**	0.000359	36.64	SW
Middle Sheyenne	**24750**	0.0358	36.93	SW
Forest	**5084000**	0.00582	26.47	SW
Forest	**5085000**	0.003883	21.41	SW
Forest	**11090**	0.01177	29.32	SW
Forest	**13169**	0.004282	10.60	GW
Forest	**13170**	2.63E-05	16.29	GW
Forest	**19831**	0.1115	3.65	GW

3.2.4 Wilcoxon Signed Rank Test for significant differences in salinity during 2001-2010 compared to 2011-2020

The results for the Wilcoxon Signed Rank Test for both the Middle Sheyenne and Forest watershed have P-values that are <<0.01 (see table 6). Therefore, we can reject the null hypothesis and can say with 99% certainty that for both watersheds, there is an increase in electrical conductivity over a period of 10 years for data spanning from 2001 to 2020. This signifies that there are overall higher salinity values during period 2 in comparison to period 1 for both watersheds. With higher salinity values during period 2, there may be more salinity threshold exceedances occurring, which will be further explored in section 2.

Table 6**:** Wilcoxon Signed Rank Test Results with W and P-Values for both Middle Sheyenne and Forest watershed.

Watershed	W	P-Value
Middle Sheyenne	1088	0.000351
Forest	835.5	5.63E-07

3.3. Crop acreage changes 2001-2020

For both watersheds, corn, soybean, and spring wheat have the largest acreage over the twenty-year period (see figure 11). For Middle Sheyenne, the largest crop acreage percentage increase between 2001-2010 and 2011-2020 is in alfalfa, corn, and soybean. Whereas the largest percentage decrease during the analysed period occurred in potato, sunflower and barley (see figure 12).

In the Forest Watershed, the largest percentage increase in acreage occurred for corn, dry beans, and soybeans. Significant acreage decreases occurred for barley, spring wheat, and sunflower between the periods of 2001-2010 and 2011-2020 (see figure 12). An interesting observation is that both watersheds experience notable increases in moderately saline-sensitive crops and a reduction in saline tolerant crops. For instance, this can be primarily seen in the 99% and 81% increases in corn and the 21% and 30% increases in dry beans.

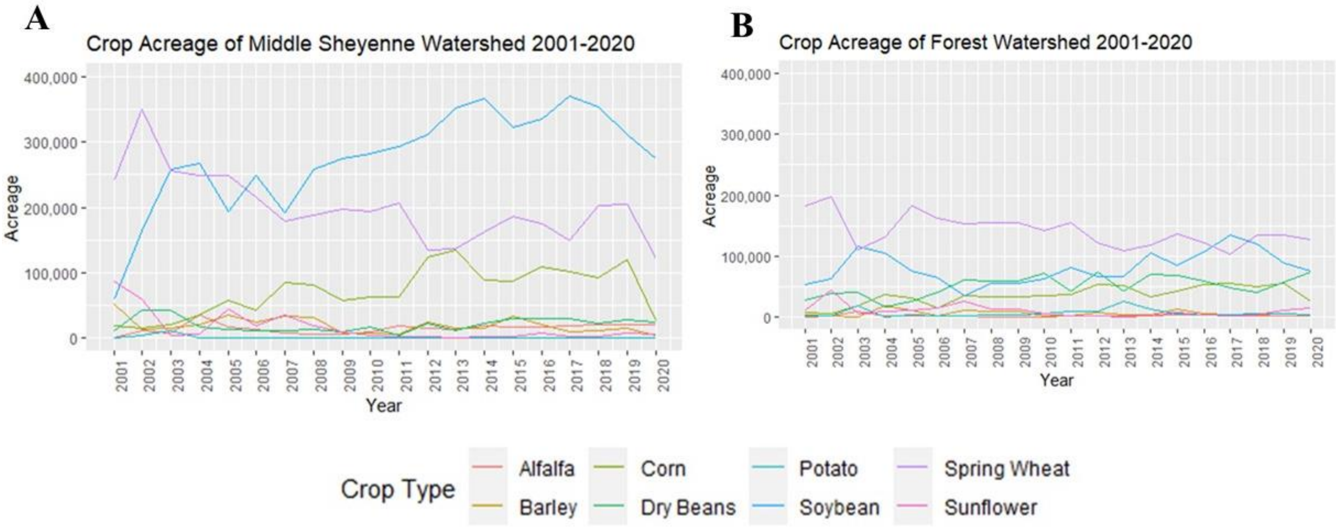


Figure 11: A) Crop acreage change for Middle Sheyenne, 2001-2020. B) Crop acreage change for Forest watershed, 2001-2020.

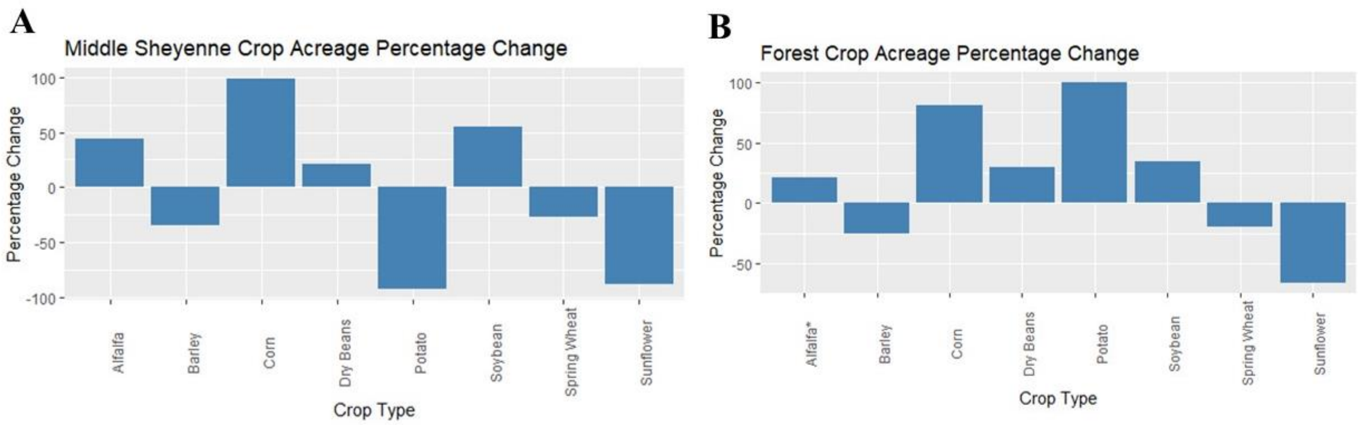


Figure 12: Bar charts showing the Crop acreage percentage change between 2001-2010 and 2011-2020. A) For Middle Sheyenne watershed. B) For Forest watershed.

3.3.1 Subbasin crop acreage changes

Subbasin analysis of crop acreage changes for Middle Sheyenne shows slight differences in percentage changes. Both upper and lower splits of the watershed see a significant acreage increase for corn, alfalfa, and soybeans (see A.6). For dry beans, the lower half of the watershed experiences a 32% increase, whereas the upper half sees no change in acreage (see figures 13 & 14). Furthermore, both subbasins show a large decrease in potatoes, sunflower, and barley. The subbasin analysis shows the same observed trend where relatively saline sensitive crop acreage increases, whereas saline tolerant crops decline over the twenty-year period.

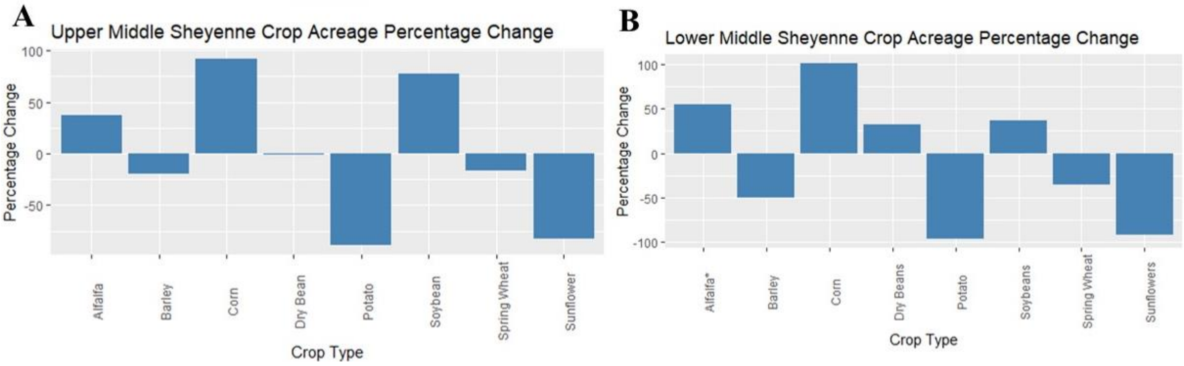


Figure 13: Bar charts showing the Crop acreage percentage change between 2001-2010 and 2011-2020. A) For the Upper-half of Middle Sheyenne watershed. B) For lower-half of Middle Sheyenne watershed.

Subbasin analysis of the Forest watershed shows a slight difference between the upstream and downstream split. The largest increase for the left side of the watershed shows increases in corn, dry beans, and soybean. The right side of the watershed sees large increases in alfalfa, corn and potato. Crop acreage decreases are similar for both sides of the watershed, with sunflower, spring wheat, and barley having the largest acreage decline (see figures 13 & 14).

Overall, corn acreage has drastically increased in both halves of the watersheds. Furthermore, there are notable acreage increases for alfalfa and dry beans for nearly all evaluated subbasins (see figures 13 & 14). Both subbasins have similar decreases in sunflower, spring wheat, and barley. There appears to be a trend for both Forest and Middle Sheyenne that the largest increases in crop acreage belong to the moderately saline sensitive category, and the largest acreage decreases are in predominantly saline tolerant crops.

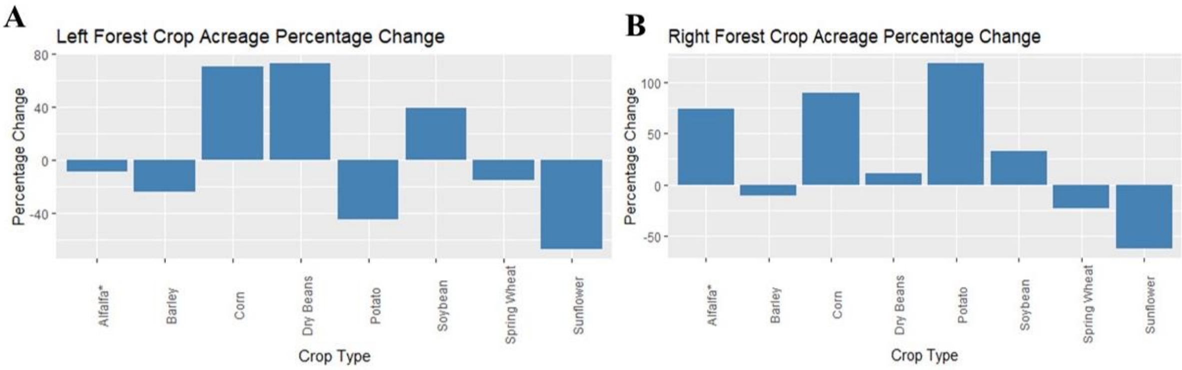


Figure 14: Bar charts showing the Crop acreage percentage change between 2001-2010 and 2011-2020. A) For the left-half of Forest watershed. B) For right-half of Forest watershed.

3.4 Crop salinity threshold exceedance

3.4.1 Middle Sheyenne

Crop salinity tolerance lines presented in figure 15 show nearly all the analysed surface water sites regularly exceed the salt tolerance levels for dry beans and potatoes; the higher tolerance levels of corn and alfalfa are exceeded for a few sites. Downstream sites on the Sheyenne River (380009 & 24750) have peaks that surpass the alfalfa threshold. Upstream surface water monitoring stations show lower saline conditions, though the dry beans and potato salt tolerance levels are often exceeded. Surface monitoring stations located on the tributaries have the lowest salinity values but still, frequently exceed the dry beans tolerance level.

A temporal trend in crop threshold salinity exceedances is evident by observing the increased number of peaks in electrical conductivity crossing the threshold lines for all sites occurring between 2011-2020. Furthermore, there appears to be a seasonality aspect in these sites through the peaks and troughs in electrical conductivity occurring during the same seasonal period.

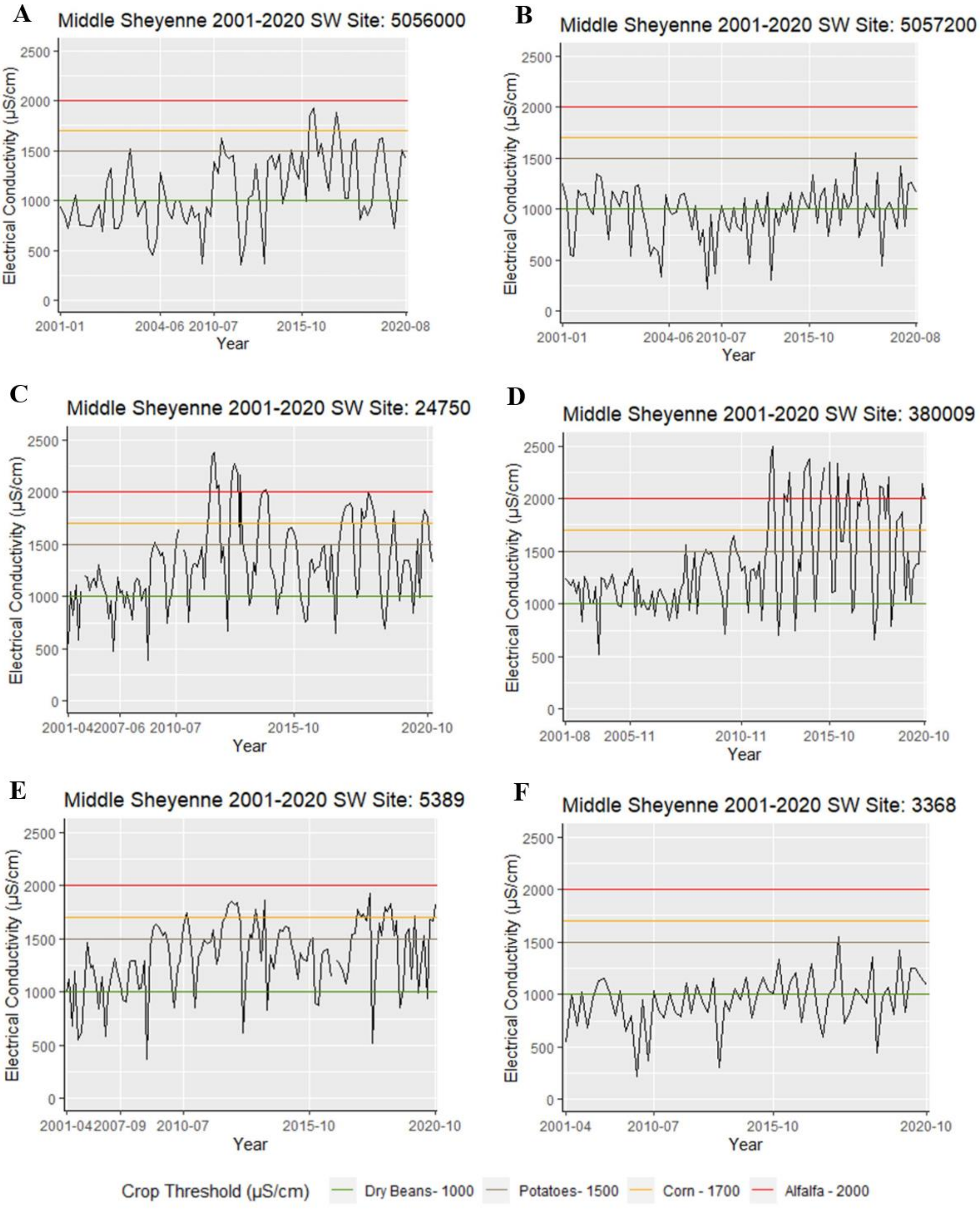


Figure 15: Monthly salinity levels (EC; μS/cm) during the study period and crop-specific exceedance levels for the Middle Sheyenne watershed. A) SW site: 5056000. B) SW site 5057200. C) SW site 24750. D) SW site 380009. E) SW site 5389. F) SW site 3368.

For all four crop types, it is observed from the boxplots (figure 16) that there tends to be a larger proportion of sites with electrical conductivity readings exceeding the crop threshold in period 2 compared to period 1. For alfalfa, which has the highest exceedance threshold of these crops, there is no exceedance during period 1 and a low exceedance percentage in period 2. In contrast, beans have the lowest threshold, and has some exceedance in period 1 with mean percentage ~60%, and a higher exceedance percentage in period 2, of ~80%. Interestingly with corn and potato crops sees the greatest shift in the percentage exceedance over the two periods. Both crops have very low exceedance in period 1 <10%, but in period 2 exceedance is much higher. Potato during period 1 has an exceedance of 8% during period 1 but during period 2 exceedance is at 33%. Corn sees a significant change as 1% is exceeded during period 1 and in period 2 this shifts to 51%.

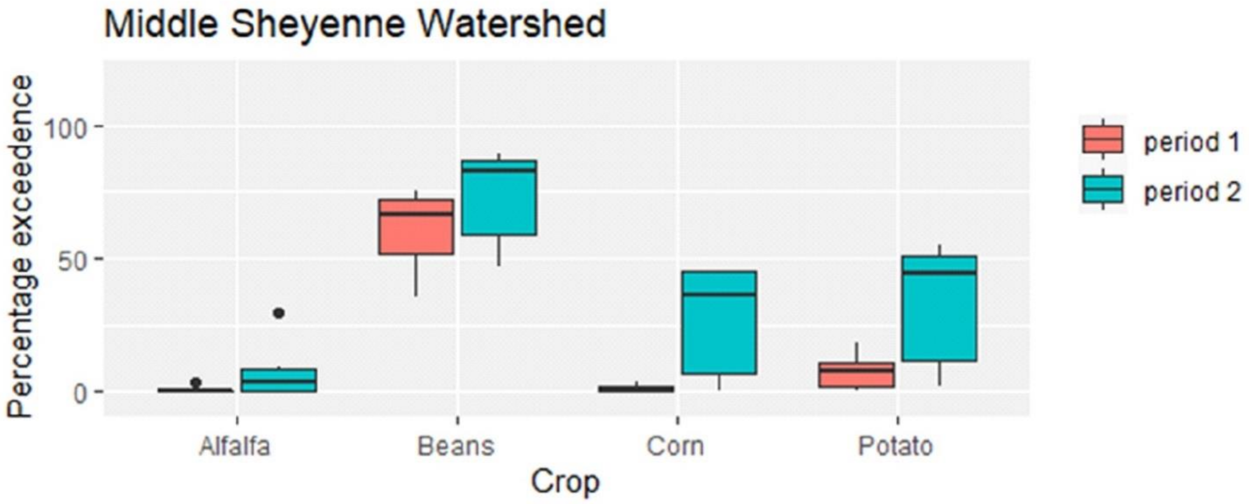


Figure 16: Exceedance boxplots for saline-sensitive crops in the Middle Sheyenne watershed for periods 1 (2001-2010) & 2 (2011-2020). These show the percentage of which salinity data at each surface water station exceed the crop thresholds. The box is made up of the lower quartile (Q1), the upper quartile (Q3) and the line represents the mid-point (median) of the data. The whiskers show the lower 25% of scores and upper 25% if scores. The dots represent outliers that are values outside the boundary of the whiskers.

3.4.2 Forest

A similar pattern of surface water stations frequently exceeding the dry beans salinity threshold also occurs in the Forest watershed. Additionally, it is also observed that a greater number of instances of electrical conductivity peaks exceeding the potato and corn threshold occur during period 2 (see figure 18) than in period 1. The alfalfa salinity threshold is not exceeded for any sites during both periods of analysis. A cross watershed comparison with the Middle Sheyenne watershed shows lower electrical conductivity levels of surface water in the Forest watershed.

Groundwater sites show lower average electrical conductivity levels compared to surface water sites. None of the groundwater well sites surpass any crop salinity tolerance thresholds but contain a gentle increase in electrical conductivity over the twenty years. Though, groundwater monitoring stations 13170 and 13169 are nearing the dry beans threshold.

For the Forest watershed, there are similar but less drastic differences between the two periods. There is still an increase in exceedance for beans, although some sites record zero exceedance over both periods. There is indeed an increase for corn and potato, but it is less significant than the results for Middle Sheyenne.

It should be noted that some of the box plots appear quite long; this occurs when half of the sites in the watershed exhibit high exceedance percentages whilst the other half exhibit percentages of almost zero. For example, in the forest watershed, beans period 2 boxplot, there are three sites with ~80-90% exceedance and other three sites with ~0-10%. This may be due to the lower groundwater EC values recorded for the Forest watershed.

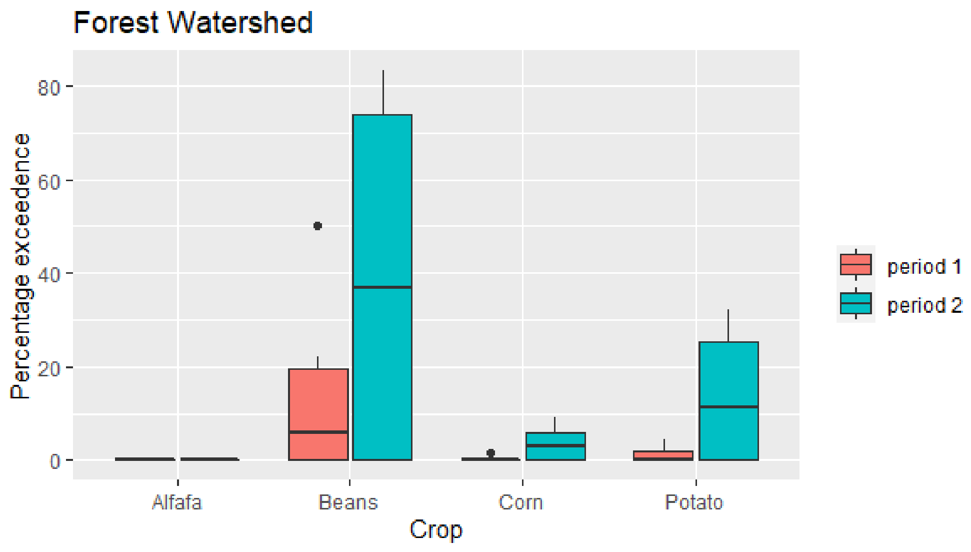


Figure 17: Exceedance boxplots for saline-sensitive crops in the Forest watershed for periods 1 (2001-2010) & 2 (2011-2020). These show the percentage of which salinity data at each surface water and groundwater station exceed the crop thresholds. The box is made up of the lower quartile (Q1), the upper quartile (Q3) and the line represents the mid-point (median) of the data. The whiskers show the lower 25% of scores and upper 25% if scores. The dots represent outliers that are values outside the boundary of the whiskers.

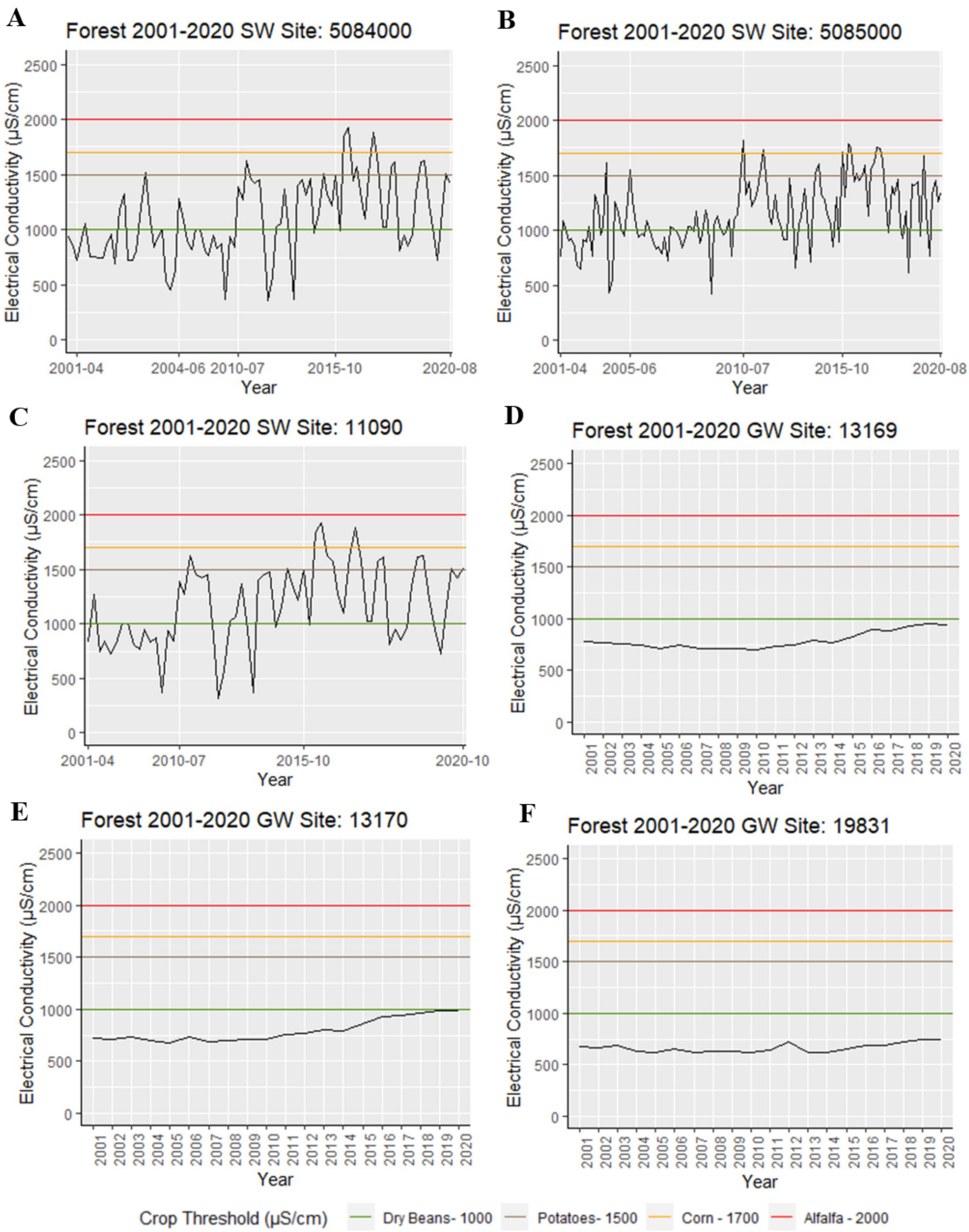


Figure 18: Monthly and yearly salinity levels (EC; µS/cm) during the study period and crop-specific exceedance levels for the Forest watershed. A) SW site: 5084000. B) SW site 5085000. C) SW site 11090. D) GW site 13169. E) GW site 13170. F) GW site 19831.

3.5 Soil salinity exceedance

3.5.1 Middle Sheyenne

Aggregated electrical conductivity from various soil samples show the spatial heterogeneity of salinity in soil. High electrical conductivity values are observed at 30-60cm (see figure 19), which is the effective rooting depth for potatoes. The highest recordings are located upstream and near the middle of the watershed, with salinity ranging between 1201-6683µS/cm, and the lowest are observed both in the most northward and southward located stations. A similar trend is observed for deeper depths of 60-90cm for the effective rooting zone of corn and dry beans. Salinity is greatest in the middle of the watershed, with electrical conductivity ranging between 1051-6325µS/cm and upstream between 601-1050µS/cm. Salinity values around 600µS/cm are observed at the north of the watershed and also at the most southern located station. Finally, effective rooting zone depths of alfalfa at 90-120cm show reduced saline conditions, with still the central sites showing the highest range of electrical conductivity values between 701-4420µS/cm.

The upper half of Middle Sheyenne shows relatively high percentages of exceedance for all soil profile levels (see table 7). Starting with the highest rooting zone of 30cm to 60cm for potatoes, 62% of observed electrical conductivity readings exceed the 1000µS/cm yield deduction threshold. The lower profiles between 60cm to 90cm also have 50% of observations exceeding the dry beans threshold and 25% exceeding corn. At the lowest profile of 90cm to 120cm, high electrical conductivity readings persist, and 62% of observations at this level exceed the alfalfa threshold of 2000µS/cm.

When observing table 7, the lower half of Middle Sheyenne appears to display contrasting results where the exceedance percentage is given as 0%. This can be explicated as less soil salinity data is available for the lower half of the watershed for all profiles. For the available data in the lower watershed, for all profiles (30-60cm, 60-90cm, and 90-120cm), electrical conductivity does not exceed any crop threshold values (see table 7 and figure 19).

Table 7: Salinity tolerance threshold exceedance for each crop at the effective rooting zone depths (cm) for both watersheds.

Watershed	Subbasin	Crop	Rooting Zone Depth (cm)	% Exceedance
Forest	Right	Potatoes	30 to 60	64%
Forest	Right	Dry Beans	60 to 90	81%
Forest	Right	Corn	60 to 90	74%
Forest	Right	Alfalfa	90 to 120	81%
Forest	Left	Potatoes	30 to 60	0%
Forest	Left	Dry Beans	60 to 90	0%
Forest	Left	Corn	60 to 90	0%
Forest	Left	Alfalfa	90 to 120	0%
Middle Sheyenne	Upper	Potatoes	30 to 60	62%
Middle Sheyenne	Upper	Dry Beans	60 to 90	50%
Middle Sheyenne	Upper	Corn	60 to 90	25%
Middle Sheyenne	Upper	Alfalfa	90 to 120	62%
Middle Sheyenne	Lower	Potatoes	30 to 60	0%
Middle Sheyenne	Lower	Dry Beans	60 to 90	0%
Middle Sheyenne	Lower	Corn	60 to 90	0%
Middle Sheyenne	Lower	Alfalfa	90 to 120	0%

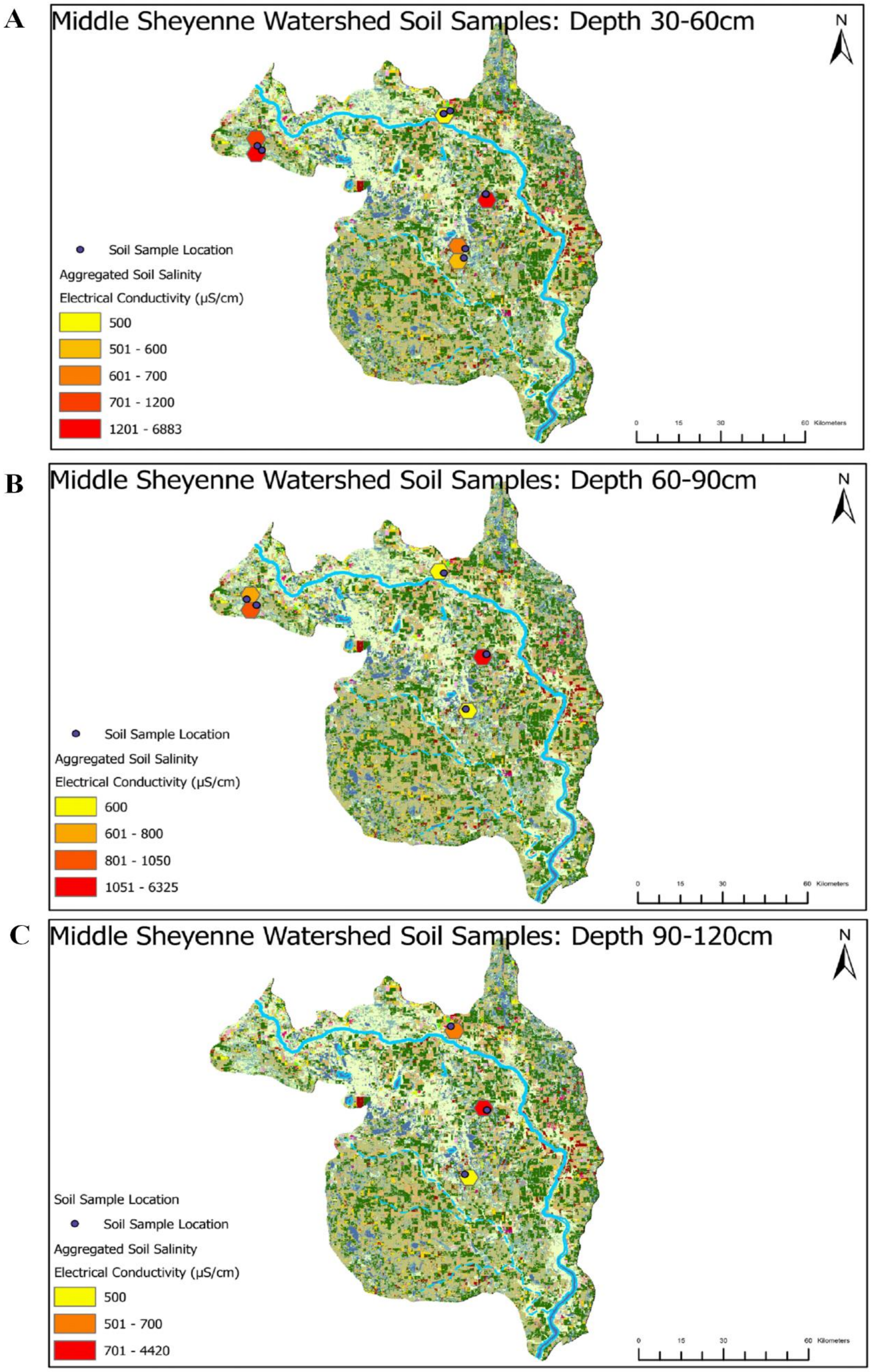


Figure 19: Aggregated soil electrical conductivity values at various effective rooting zone depths. A) Depth 30-60cm B) Depth 60-90cm C) Depth 90-120cm.

3.5.2 Forest

Aggregated soil electrical conductivity values at all effective rooting zone depths show higher saline conditions in the Forest watershed than in the Middle Sheyenne watershed (see figure 20 and table 7). Soil salinity samples at 30-60cm show high electrical conductivity values between 5301-9555µS/cm at the far east of the watershed, which largely exceeds the salinity tolerance thresholds for potatoes. Nearly all observations at the effective rooting depth for potatoes surpass the tolerance threshold further east of the watershed. This is also similar in deeper soil depths of 60 to 90cm for dry beans and corn. Salinity conditions at this depth can reach up to 8941-13673µS/cm at the far east of the watershed. Furthermore, at this depth, the highest salinity conditions are observed. Similar trends are observed for the 90-120cm effective rooting zone depth of alfalfa, and most observations are lowest towards the west and increase eastward. Overall, soil salinity conditions surpass each crop's crop salinity tolerance thresholds.

Soil salinity exceeding crop thresholds shows higher exceedance percentages occurring at the Forest watershed. For the soil profile 30cm to 60cm, 64% of electrical conductivity readings exceed the 1500µS/cm potato threshold. The lower profile of 60cm to 90cm contains higher exceedance values, with 81% of observations exceeding the 1000µS/cm dry beans threshold and 74% exceeding the 1700µS/cm corn threshold. Finally, at the lowest profile of 90cm to 120cm, 81% of observations exceed the 2000µS/cm alfalfa threshold (see table 7). However, only two soil salinity profile readings are available for the left side, and neither of the electrical conductivity readings exceeds any threshold.

The east of the Forest watershed appears to have the highest occurrence of soil salinity values that exceed crop thresholds. This might suggest that saline soils persist at these soil sample sites, and percentage exceedance of soil salinity is seen to increase as the depth increases (table 7) (see figure 20).

A B C

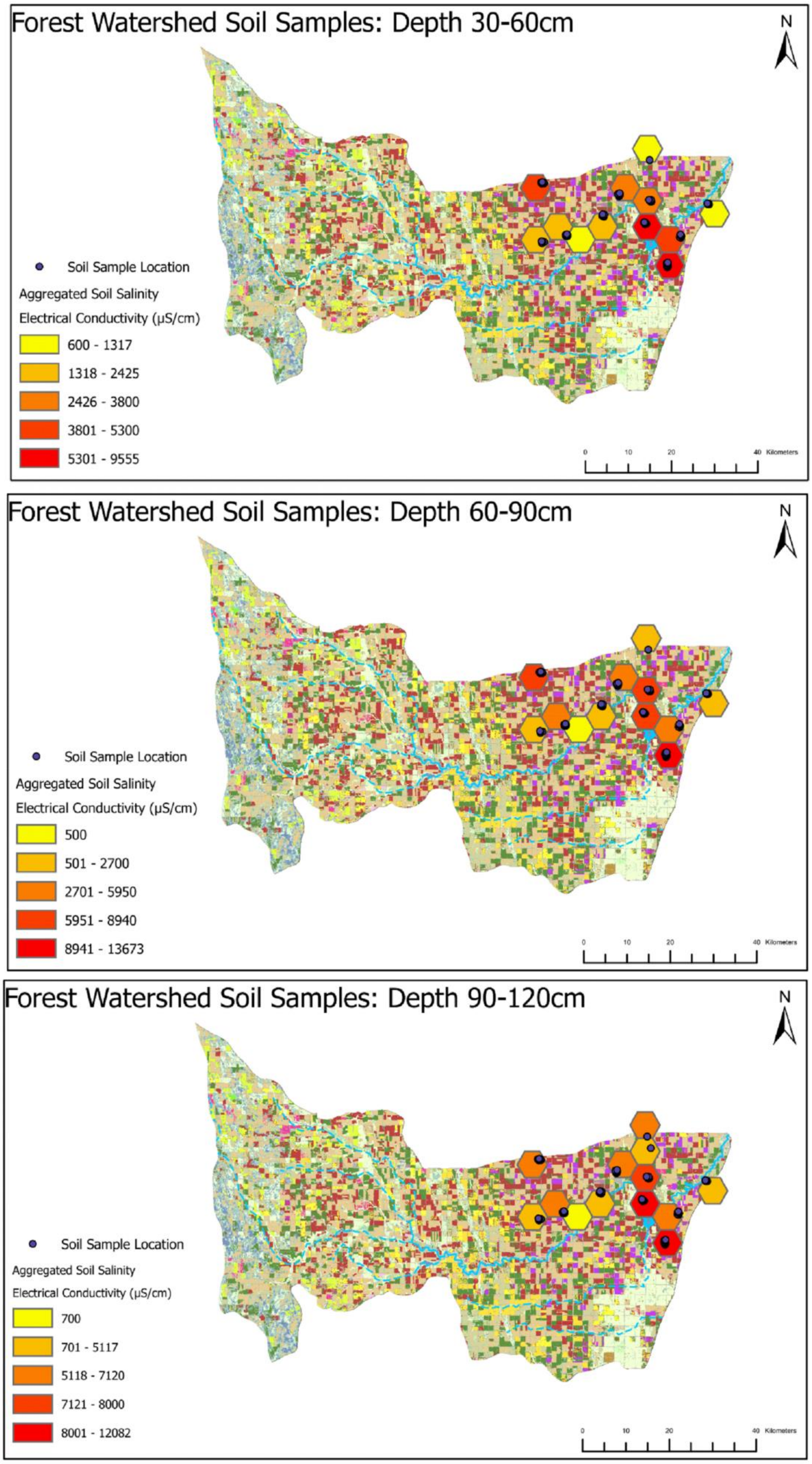


Figure 20: Aggregated soil electrical conductivity values at various effective rooting zone depths. A) Depth 30-60cm B) Depth 60-90cm C) Depth 90-120cm

3.6 Acreage and yield data comparison

From the previous section we observed that salinity levels for both watersheds often exceeded crop salinity thresholds for dry beans. Yield decrease data from Franzen (2003) has been used to find the potential production for both dry beans and potatoes. Tables 8 and 10 show the percentage of maximum yield and potential production (kg) for all stations in both watersheds. The average electrical conductivity for both periods and threshold values are used to calculate the potential production.

3.6.1 Forest Watershed

We can observe that many surface water stations have averages exceeding the dry beans threshold. In particular, surface water station 5085000 exceeds in both periods, and potential yield in this area for dry beans can drop by 5% between periods 1 and 2 (see table 8). For the other surface water sites where salinity exceeds the threshold during period 2, there is also a potential reduction of dry beans yield by approximately 5%. The groundwater sites do not exceed any thresholds, and the maximum production is unchanged. Averaging all the electrical conductivity data and separating it into periods one and two, the Forest watershed appears to maintain maximum production for all the crops analysed other than dry beans (see table 9).

Table 8: Forest watershed estimated maximum production and potential production (kg) after accounting for the effects of salinity for dry beans.

Site ID	Period	EC (µs/cm)	Threshold	% Yield Decrease	% of Maximum Yield	Maximum production (kg)	Potential Production (kg)
5085000	1	1012.70	1000	19	99.8	54640000	54510000
5085000	2	1258.36	1000	19	95.1	54640000	51200000
11090	1	882.5	1000	19	100.0	54640000	54640000
11090	2	1262.6	1000	19	95.0	54640000	51910000
13169	1	740.4	1000	19	100.0	54640000	54640000
13169	2	845.5	1000	19	100.0	54640000	54640000
13170	1	714.3	1000	19	100.0	54640000	54640000
13170	2	880.1	1000	19	100.0	54640000	54640000
19831	1	642.8	1000	19	100.0	54640000	54640000
19831	2	684.9	1000	19	100.0	54640000	54640000
5084000	1	899.9	1000	19	100.0	54640000	54640000
5084000	2	1254.9	1000	19	95.2	54640000	51990000

Table 9: Forest watershed maximum and potential yield summary for each crop based on average salinity values during period 1 (2001-2010) and period 2 (2011-2020).

Watershed	Crop	Period	Average EC µS/cm	Threshold	% Yield Decrease	% of Maximum Yield	Maximum production (kg)	Potential production (kg)
Forest	Beans	1	815.4	1000	19	100	54640000	54640000
Forest	Beans	2	1031.0	1000	19	99.4	54640000	54320000
Forest	Potato	1	815.4	1500	3.7	100	73090000	73090000
Forest	Potato	2	1031.0	1500	3.7	100	73090000	73090000
Forest	Corn	1	815.4	1700	4.2	100	89980000	89980000
Forest	Corn	2	1031.0	1700	4.2	100	89980000	89980000
Forest	Alfalfa	1	815.4	2000	6.1	100	580100	580100
Forest	Alfalfa	2	1031.0	2000	6.1	100	580100	580100

3.6.2 Middle Sheyenne

More EC averages are exceeded, and potential production is less for dry beans compared to the Forest watershed. For sites in the upper half of the watershed (505600 & 5389), we observe approximately a 3% reduction in potential yield during period 1, which increases to ~10% during period 2. The greatest reduction in maximum yield occurs in the lower half of the watershed at sites 380009 and 24750. For both of these sites, the salinity threshold for dry beans is exceeded for periods 1 and 2. Site 380009 has a yield decrease of ~3% during period 1, which noticeably increases to ~12% by period 2. Site 24750, on the other hand, has ~8% decrease for period 1 and reduces by less than 1% for period 2 (see table 10).

Finally, SW sites 5057200 and 3368 located on a tributary, maintain maximum potential yield for dry beans. However, during period 2 both sites EC values are near the dry beans threshold which might be surpassed in the near future.

The Middle Sheyenne also has a minor decrease of ~3% for potatoes for SW site 380009 during period 2 (see table 11). On the whole, we see an average maximum yield decline of 2% for dry beans during period 1. This decline increases to nearly 8% during period 2. Average salinity for periods 1 and 2 does not exceed other focused crops. However, the frequency of exceedance during period 2 appears to increase, as seen in the previous section (see table 11).

Data agrees with the temporal shift that the effects of salinity are more pronounced during period 2, and regarding spatial patterns, downstream seems to bear the most significant impact of rising salinity.

Table 10: Middle Sheyenne watershed estimated maximum production and potential production (kg) after accounting for the effects of salinity for dry beans.

Site ID	Period	EC (µs/cm)	Threshold	% Yield Decrease	% of Maximum Yield	Maximum production (kg)	Potential Production (kg)
5056000	1	1127.8	1000	19	97.6	173500000	169200000
5056000	2	1497.1	1000	19	90.6	173500000	157100000
5057200	1	928.1	1000	19	100.0	173500000	173500000
5057200	2	985.3	1000	19	100.0	173500000	173500000
380009	1	1163.1	1000	19	96.9	173500000	168100000
380009	2	1616.4	1000	19	88.3	173500000	153100000
24750	1	1402.0	1000	19	92.4	173500000	160200000
24750	2	1432.4	1000	19	91.8	173500000	159200000
5389	1	1172.8	1000	19	96.7	173500000	167800000
5389	2	1464.9	1000	19	91.2	173500000	158100000
3368	1	826.9	1000	19	100.0	173500000	173500000
3368	2	985.6	1000	19	100.0	173500000	173500000

Table 11: Middle Sheyenne watershed maximum and potential yield summary for each crop based on average salinity values during period 1 (2001-2010) and period 2 (2011-2020).

Watershed	Crop	Period	EC (µs/cm) average	Threshold	% Yield Decrease	% of Maximum Yield	Maximum production (kg)	Potential Production (kg)
Middle Sheyenne	Beans	1	1103.45	1000	19	98.0	17350000	17000000
Middle Sheyenne	Beans	2	1330.26	1000	19	93.7	17350000	16260000
Middle Sheyenne	Potato	1	1103.45	1500	3.7	100	3346000	3346000
Middle Sheyenne	Potato	2	1330.26	1500	3.7	100	3346000	3346000
Middle Sheyenne	Corn	1	1103.45	1700	4.2	100	91190000	91190000
Middle Sheyenne	Corn	2	1330.26	1700	4.2	100	91190000	91190000
Middle Sheyenne	Alfalfa	1	1103.45	2000	6.1	100	3919000	3919000
Middle Sheyenne	Alfalfa	2	1330.26	2000	6.1	100	3919000	3919000

4. Discussion

Freshwater salinity is posing an increasing threat to agricultural production across regions across the United States (Kaushal et al. 2021). This study has attempted to evaluate the complex spatiotemporal salinity trends of watersheds in the Red River Valley of North Dakota. The results present an increasing downstream salinity trend for surface water in both watersheds. Groundwater monitoring stations, on the other hand, did not follow the same spatial trend. The results of increasing downstream salinity and greater potential yield reductions agree with other studies. For example, Morway & Gates (2012) study of the Lower Arkansas River Valley (LARV) in Colorado, Alam et al. (2021) on the White River in Indiana, and Laceby et al. (2019) in Alberta, Canada though at a river basin scale rather than a watershed scale. However, the results from this study differ since salinity is significantly increasing even at a watershed scale.

Temporal salinity trends conducted utilising statistical tests that investigated the relationship between electrical conductivity and time confirmed a monotonic upward trend in salinity for virtually all sites, and surface water had the greatest increasing rate of annual salinity. Wilcoxon tests further show that there is a significant increase in salinity for both watersheds during the latter time period of 2011-2020. This reflects national trends of salinity seen by (Kaushal et al. 2018).

The effects of salinity on agricultural crops are potentially amplified by the shifts in crop types and acreage to more saline-sensitive crops occurring in both watersheds, which aligns with regional trends. Over the past twenty years, significant crop shifts to corn were observed in the Middle Sheyenne and Forest watershed. This may be due to commodity prices and the recent boom in the biofuels industry creating economic incentives to cultivate corn in the Midwest (Green et al. 2015; Lark et al. 2015; Wright et al. 2013; Vadas et al. 2008). The cropland expansion of corn is a concern, especially in North Dakota, as results show irrigation water sources are becoming more saline, potentially resulting in high drainage maintenance costs and economic loss.

Integrating crop salinity threshold information and salinity data from all monitoring stations reveals that the dry beans and potato thresholds are regularly surpassed for surface water sites. Furthermore, the higher salinity thresholds of corn and alfalfa are surpassed more frequently, especially at downstream sites between 2011 and 2020. The frequent exceedance of the dry beans threshold is a concern since North Dakota is the largest producer in the United States (USDA, 2021). Available soil salinity data shows that the effective rooting zones for these saline-sensitive crops already possess very saline conditions, particularly in the Forest watershed.

The various sources and existing conditions of salinity can eventually culminate, resulting in a loss of agricultural production in both watersheds. Already, the Middle Sheyenne watershed is expected to contain a 10% yield deduction in dry beans due to surface water salinity conditions. Additionally, the Forest watershed sees approximately a 5% loss in dry beans production around surface water sites during period 2.

Regarding uncertainties within this study, monitoring stations and probes providing readings of electrical conductivity must be regularly maintained in order to minimise observational errors and possibly be a source of uncertainty (USGS, 2019). Another factor of uncertainty is the role of other variables in affecting electrical conductivity readings such, as temperature anomalies, regional weather patterns, nonpoint source pollution, and local anthropogenic disturbances coinciding with sample collection times (McNeil & Cox, 2000; Kunkle & Wilson, 1984; USEPA, 1982).

Furthermore, spatial and temporal gaps in soil salinity data create another area of uncertainty. This is particularly seen in the south of the Middle Sheyenne watershed and west of the Forest watershed. The few numbers of ground measurements in these areas and parts of North Dakota are due to the high costs and labour intensiveness of soil salinity data collection (Lobell et al. 2010). A similar spatiotemporal gap persists for groundwater data as there is little information of groundwater salinity conditions, especially in the southern part of the Middle Sheyenne watershed and the western part of the Forest watershed. As a result, it is difficult to observe the exact local salinity conditions particularly, at a field scale. This is important as saline groundwater discharge from bedrock aquifers situated beneath marine-derived sediments can be a cause of salinity and explain downstream trends (Strobel & Haffield, 1995).

Another uncertainty is the lack of extract annual crop yield data for the watershed. Although the acreage of particular crops is increasing, this does not suggest that yield is also increasing. Therefore, annual crop yield data at the watershed scale will be useful in evaluating the effects of salinity and investigate if the yield is increasing proportionally with acreage.

4.1 Outlook

Due to saline soils, the Red River Valley (RRV) loses around $50 million annually in agriculture (Lobell et al. 2010). Over the past decades, saline conditions have been exacerbated by persistent wet cycles and record flooding resulting in higher water tables and salt distribution throughout fields (Hadrich, 2012). Furthermore, research on climate change in the RRV projects wetter conditions resulting in rising water tables and coupled with crop shifts to more shallow-rooted crops (corn), resulting in increased salt accumulation in the rooting zones (Corwin, 2020). Research by Lobell et al. (2010) on the Minnesota side of the RRV showed that there had been a 30% increase from 1979 to 2007 in agricultural land with soil salinity higher than 2000µS/cm. Salinity control and alternative salt-tolerant crops are therefore necessary for preventing yield loss.

Crop managers must effectively control the flow of saline water to prevent it from reaching the root zone and causing yield decreases. Hadrich (2012) provided several options to address salinity in North Dakota. These options are to invest in tile drainage, plant saline tolerant crops, or take no action and have less productive land.

Tile drainage is a method of soil management that carries salt away from fields using tile lines and drainage canals. Additionally, tile drainage can reduce machinery costs by improving field conditions and providing more consistent yields. However, the installation of tile drainage requires a moderately high upfront investment. Installation costs approximately $800/acre, and the effectiveness depends on soil type, depth, and topography (Hadrich, 2012).

Another method if tile drainage is not economically viable is crop switches. In the previous sections, dry beans, potatoes, and corn are all considered saline-sensitive crops. Switching to more saline tolerant crops such as spring wheat or barley can be an option. However, as seen in section 3.3, over the past 20 years, corn acreage has increased by 98% in Middle Sheyenne and 81% in Forest Watershed. This is because corn has one of the highest profit per acre margins compared to other crops. On the other hand, barley has one of the lowest profit per acre margins. According to Hadrich (2012), even at a 10% yield reduction, corn still has slightly higher profitability than barley. This shows that the profitability of crops has a major role in agriculture, and as corn prices are higher than ever, it will be increasingly more challenging to switch out of corn. If the yield of saline-sensitive crops begins to decline, a recommendation is to switch to sunflowers.

By evaluating the physical and economic factors, a recommendation could switch to sunflowers or canola as a solution. Sunflowers have a moderately high salinity tolerance threshold of 4800µS/cm, and canola is saline tolerant with a threshold of 9700 µS/cm (Franzen, 2003). As of this year, sunflower is priced at 32 dollars/cwt and canola at 37 dollars/cwt (USDA, 2022). Although both alternatives bring in less profit of dry beans at 44 dollars/cwt, this is compensated by diminishing the loss of yields due to salinity.

4.2 Suggestions for future studies

The integration of greater spatial and temporal soil salinity datasets can be further developed for this study. Initial steps to this were conducted by Lobell et al. (2010) study on the Red River Valley between North Dakota and Minnesota. The study integrated soil salinity field datasets with MODIS satellite data to map the distribution of soil salinity along the Red River Valley. This dataset could be perhaps adapted to Forest and Middle Sheyenne watersheds to gather in-depth information on the spatial distribution of soil salinity. Furthermore, future studies can utilise this data and evaluate the majority of North Dakota's agricultural region.

Further developments to this study can include the seasonal variations of electrical conductivity associated with water data in the North Dakota watersheds. Conducting a Seasonal Kendall test and a Wilcoxon test separating hydrological seasons can provide information on the seasonality of salinity. Ground-truthing and the creation of field salinity maps can help improve the resolution of soil salinity data. Finally, interviews with community stakeholders are always crucial in providing local knowledge on salinity hotspots and local salinity management.

5. Conclusion

The research aims of this study were: to investigate the spatial and temporal salinity levels in the selected agricultural watersheds over the period 2001-2020, to investigate the extent to which crop-specific thresholds are exceeded in the investigated crop areas, and to identify any correlations between historical salinity levels and crop land-use and/or yield changes in these regions.

The first research aim was addressed by evaluating long-term temporal salinity levels both visually and statistically. The study found that conditions across the watersheds are getting progressively more saline, and a significant increase in salinity can be observed by comparing salinity data from 2001-2010 with data from 2011-2020. Further statistical analysis through a Mann-Kendall test and Sen’s Slope Estimator revealed that all twelve sites contained a significant monotonic upward temporal trend for salinity, and electrical conductivity is increasing at a noteworthy yearly rate for both surface water and specific groundwater sites.

The spatial patterns of salinity levels were also investigated by utilising additional sites to evaluate the salinity conditions throughout both watersheds. It was found that surface water salinity increased downstream along the main rivers, and the highest electrical conductivity values were found at the end of the main rivers for both watersheds. Soil data showed very saline conditions at each effective rooting zone depth of saline-sensitive crops, though there is a lack of soil salinity data which is a limiting factor in investigating the complete spatial extent of salinity in both watersheds. Salinity in both watersheds is significantly increasing and indicates that surface water used for agriculture is becoming progressively more saline.

The second research aim was addressed by integrating the temporal salinity observations and crop yield threshold values. It was found that the dry beans salinity threshold was regularly exceeded in both watersheds. Downstream sites appeared to have higher peak salinity values, with higher peaks occurring in all surface water sites during 2011-2020. Boxplots of both watersheds showed this pattern where more crop thresholds were exceeded during the period 2011-2020 when compared to 2001-2010. In particular, low threshold values of dry beans, potatoes, and corn showed greater threshold exceedance percentages. Soil salinity observations showed high percentage exceedance values at varying depths. These results show that the dry beans salinity threshold is mainly surpassed, and salinity levels are starting to surpass other saline-sensitive crops more often.

Finally, the final research question was answered by first evaluating changes in crop acreage over the 20-year period. The study found that there has been large acreage increases in saline sensitive crops and noticeable decreases in saline tolerant crop acreages for both watersheds, which is driven by economic factors. Correlations between historical salinity levels and cropland use were found by using acreage and yield data to find the maximum potential production of each saline-sensitive crop in both watersheds. Greater reductions of maximum yield percentages occurred during the period 2011-2020, and downstream sites on the Sheyenne River saw approximately a 10% reduction in the potential dry beans yield. Forest watershed also experienced the same trend of greater reductions in the potential yield of dry beans occurring in period 2 and saw similar values of a 10% potential yield decrease.

This study provides a framework for investigating the spatiotemporal trends of salinity while incorporating the crop salinity threshold data to estimate potential yield deductions at a watershed scale. The methodology can be used in comparing salinity conditions and potential yield impacts between individual watersheds or agricultural basins. This could then be integrated with long-term streamflow records to better evaluate the transportation of salinity and contributors of salinity.

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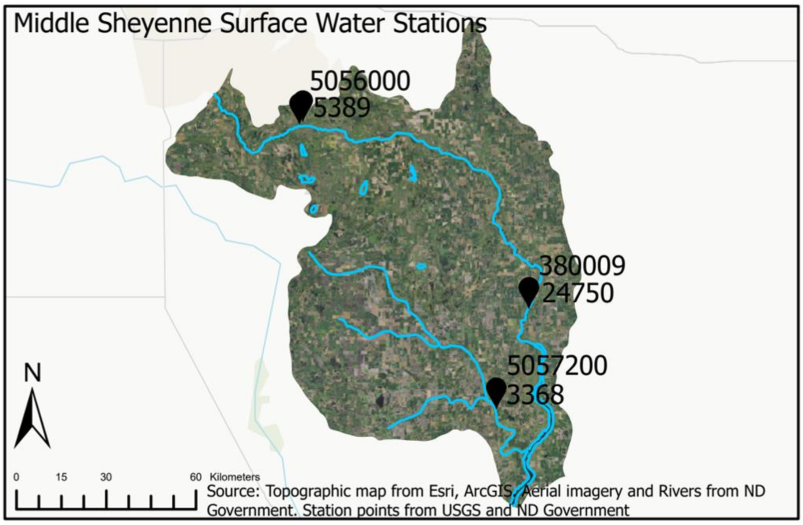
Appendix

A



B

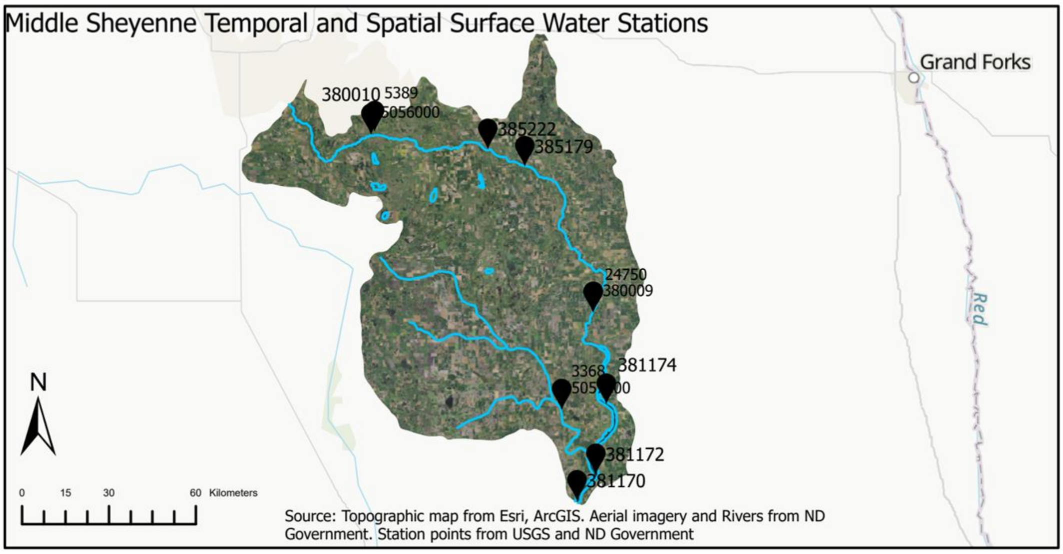


Figure A.1: A) Temporal surface water sites selected using site selection criteria for Middle Sheyenne. B) Additional SW sites to analyse spatial distribution of salinity.

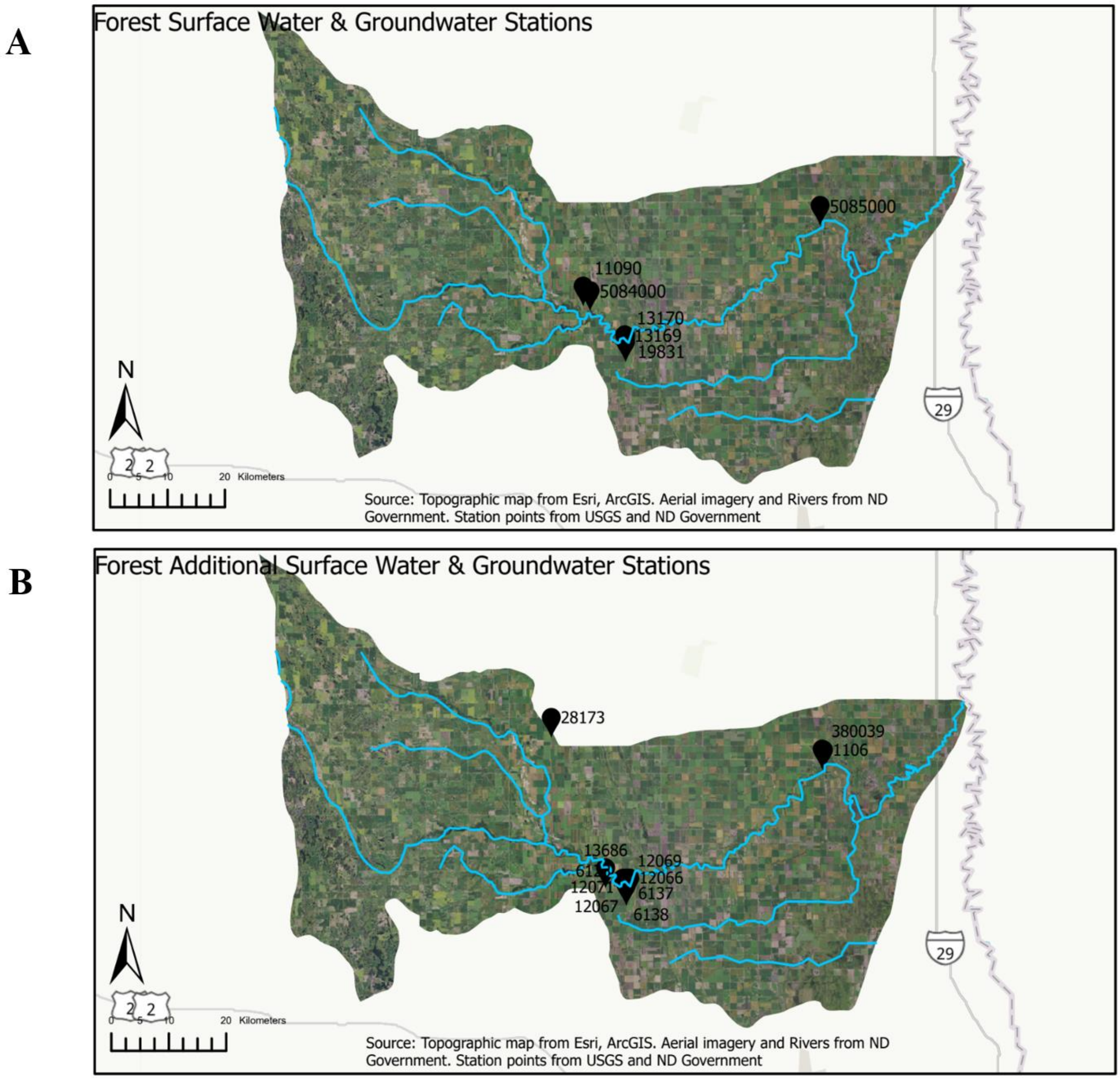


Figure A.2: A) Temporal surface water & groundwater sites selected using site selection criteria for Forest B) Additional SW & GW sites to analyse spatial distribution of salinity.

Table A.1: Site ID, with coordinates for surface water and groundwater sites within the Forest and Middle Sheyenne watersheds.

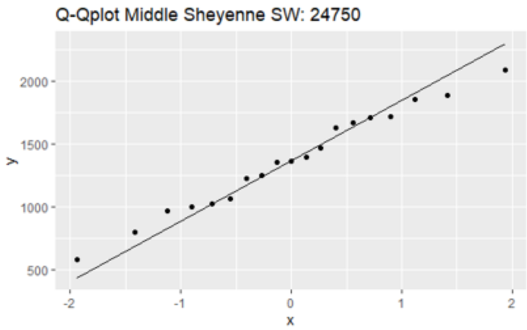
		Site ID	Longitude	Latitude			Site ID	Longitude	Latitude
Forest	GW	13686	-97.7089	48.16211	Middle Sheyenne	GW	9349	-98.5254	47.84602
		28173	-97.7938	48.31894			5363	-98.5254	47.84602
		12066	-97.6711	48.15146			9352	-98.5252	47.83194
		6137	-97.6763	48.14391		SW	385345	-98.7172	47.80526
		6138	-97.6763	48.14391			380010	-98.7172	47.80526
		12067	-97.6711	48.15147			385222	-98.3543	47.77408
		12071	-97.6763	48.14805			385179	-98.2397	47.7382333
		12069	-97.6763	48.15149			381170	-98.0775	47.03729
		6123	-97.6813	48.15147			381172	-98.019	47.09318
		13169	-97.6763	48.15115			381174	-97.9865	47.24084
		13170	-97.675	48.15038			5056000	-98.7162	47.80555
		19831	-97.675	48.14394			5057200	-98.1248	47.22916
	SW	5084000	-97.7306	48.19721			380009	-98.0278	47.43292
		5085000	-97.3701	48.2861			24750	-98.0269	47.43382
		11090	-97.7414	48.2021			5389	-98.7055	47.81115
		380039	-97.3698	48.28598			3368	-98.125	47.22923
		1106	-97.3677	48.28513					

Table A.2: Profile ID, with coordinates of soil electrical conductivity sites within the Forest watershed.

Watershed	profile_id	Longitude	Latitude
Forest	144207	-97.2797	48.20556
	144209	-97.2789	48.20639
	144205	-97.2806	48.20694
	144210	-97.2786	48.20722
	144206	-97.2803	48.20806
	144208	-97.2792	48.20806
	144211	-97.2811	48.20889
	144213	-97.2797	48.21056
	144214	-97.2794	48.21083
	144212	-97.2811	48.21139
	144215	-97.2789	48.21222
	144512	-97.5407	48.2389
	144514	-97.5364	48.24083
	144515	-97.5404	48.24084
	144516	-97.5417	48.24171
	144467	-97.2516	48.24671
	144464	-97.2537	48.24735
	144469	-97.2503	48.24877
	144489	-97.4878	48.24877
	144490	-97.4909	48.24888
	144465	-97.2533	48.24989
	144468	-97.2512	48.25004
	144491	-97.4897	48.25046
	144492	-97.4877	48.25064
	144488	-97.4912	48.25088
	144466	-97.2522	48.25121
	144493	-97.489	48.25159
	144203	-97.3264	48.26556
	144204	-97.3258	48.26556
	144202	-97.3244	48.26583
	144201	-97.3231	48.26583
	144218	-97.3236	48.26611
	144200	-97.3256	48.26639
	144199	-97.3272	48.26722
	144198	-97.3253	48.26722
	144196	-97.3261	48.2675
	144195	-97.3281	48.26806
	144197	-97.3275	48.26806
	144511	-97.4118	48.27582
	144510	-97.4155	48.27676
	144509	-97.4118	48.27745
	144508	-97.4139	48.27772
	144507	-97.4111	48.27871
	144506	-97.4146	48.27894
	144456	-97.195	48.2926
	144452	-97.1925	48.29261
	144454	-97.1937	48.29267
	144453	-97.1928	48.29369
	144455	-97.195	48.29371
	144457	-97.1963	48.29416
	144476	-97.3126	48.29667
	144477	-97.3148	48.2967
	144479	-97.3163	48.29777
	144480	-97.3137	48.29915
	144481	-97.318	48.2992
	144472	-97.3803	48.30388
	144473	-97.3791	48.30515
	144471	-97.3811	48.30567
	144474	-97.3791	48.30677
	144470	-97.3825	48.30743
	144475	-97.3791	48.30833
	144501	-97.5413	48.32169
	144502	-97.5366	48.32187
	144503	-97.543	48.32321
	144504	-97.5377	48.32347
	144505	-97.5404	48.32373
	144478	-97.3167	48.35425
	144207	-97.3092	48.33833

Table A.3: Profile ID, with coordinates soil electrical conductivity sites within the Middle Sheynne watershed.

Watershed	profile_id	Longitude	Latitude
Middle Sheyenne	149815	-98.3089	47.46472
	149816	-98.3042	47.48667
	145132	-98.2385	47.61428
	145132	-98.2394	47.61433
	145137	-98.2389	47.6145
	145136	-98.2383	47.61478
	145134	-98.2388	47.61481
	145135	-98.9546	47.71748
	152395	-98.9691	47.72778
	176794	-98.3739	47.80278
	149818	-98.3532	47.80943
	149817	-98.9701	47.7282
	149816	-99.001	47.74165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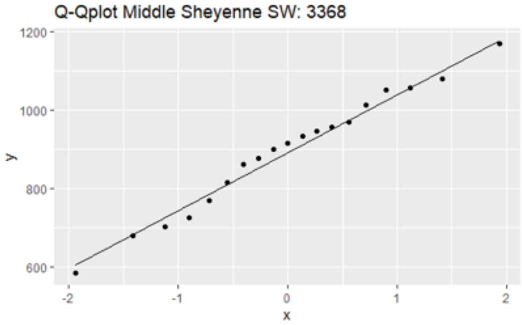
y
x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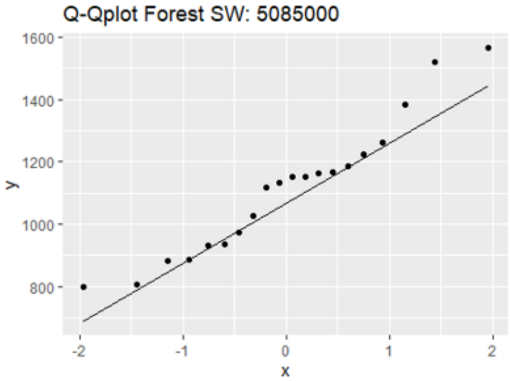
y
x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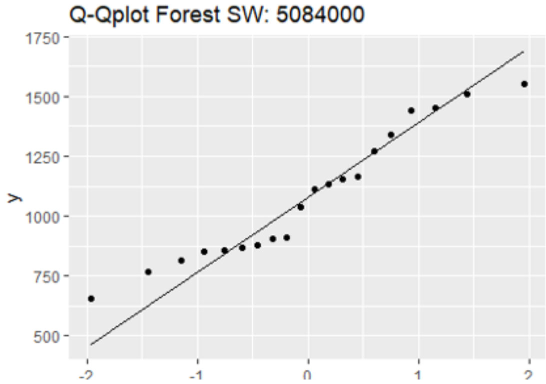
y
x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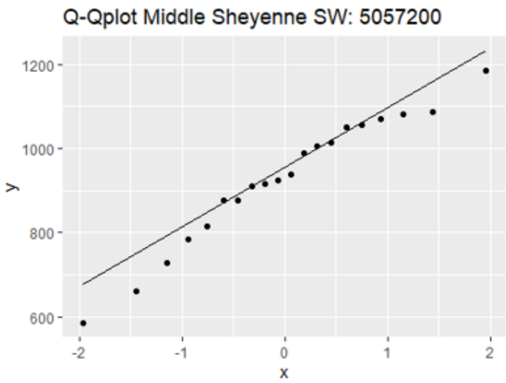
y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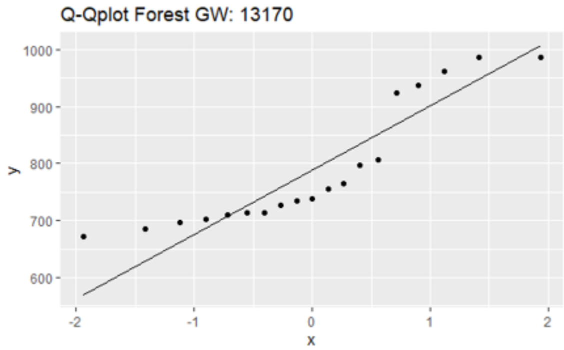
y
x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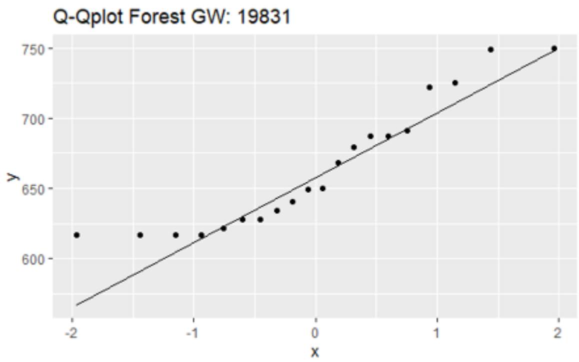
y
x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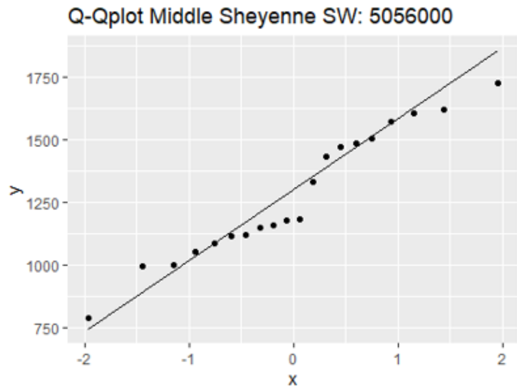
y
x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y
x

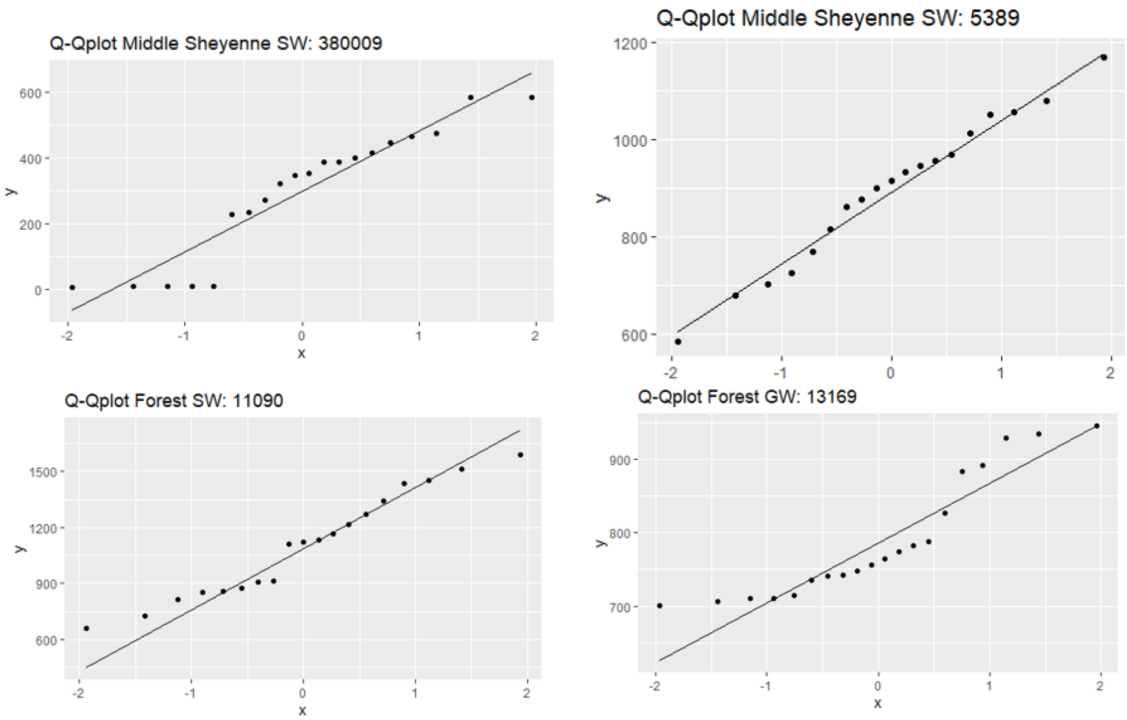
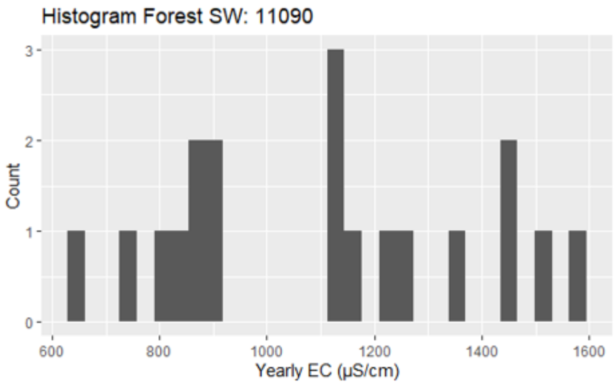
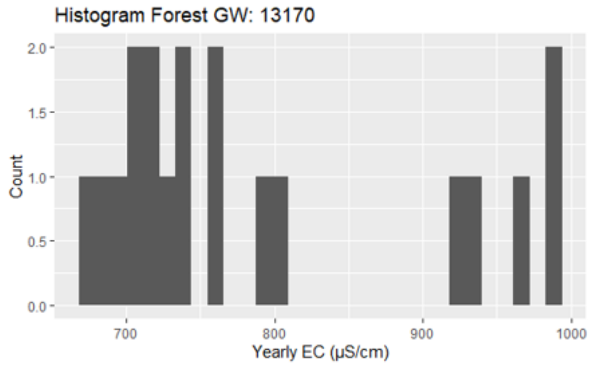


Figure A.3: QQplots of all high temporal resolution sites both surface water and groundwater showing that EC data is not normally distributed in the Forest and Middle Sheyenne watersheds.


Histogram Forest SW: 11090
Count
0
1
2
3
600
800
1000
1200
1400
1600
Yearly EC (µS/cm)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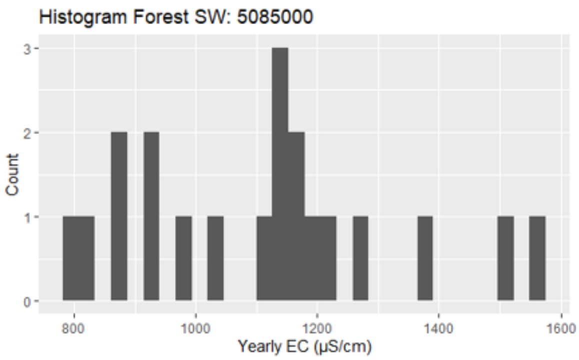
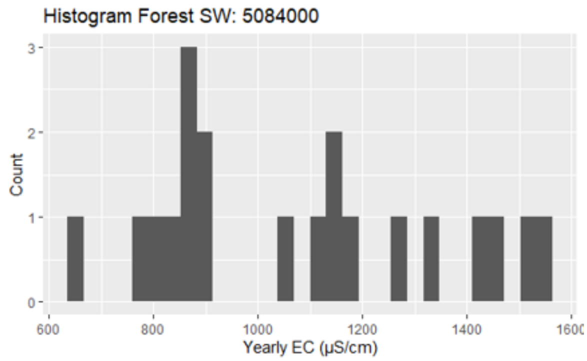
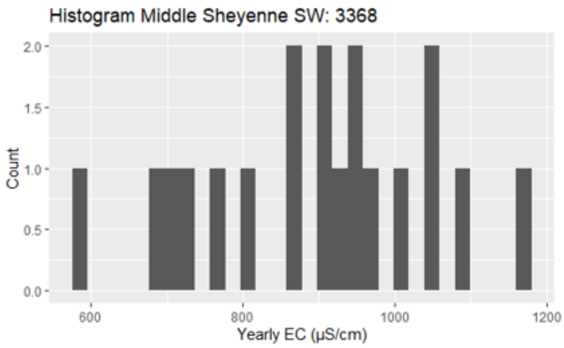
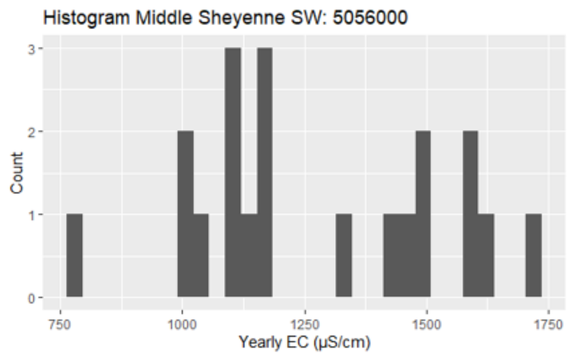
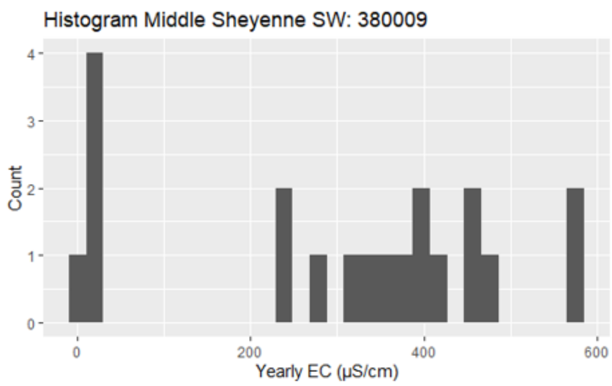
Count
0.0
0.5
1.0
1.5
2.0
700
800
900
1000
Yearly EC (µS/cm)

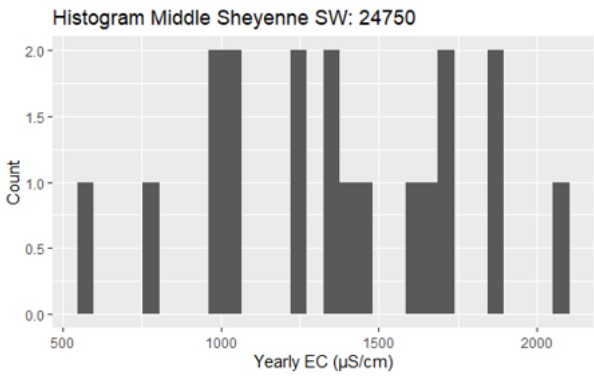

Histogram Forest SW: 5085000
Count
0
1
2
3
800
1000
1200
1400
1600
Yearly EC (µS/cm)


Histogram Forest SW: 5084000
Count
0
1
2
3
600
800
1000
1200
1400
Yearly EC (µS/cm)


Histogram Middle Sheyenne SW: 3368
Count
0.0
0.5
1.0
1.5
2.0
600
800
1000
1200
Yearly EC (µS/cm)


Histogram Middle Sheyenne SW: 5056000
Count
0
1
2
3
750
1000
1250
1500
1750
Yearly EC (µS/cm)


Histogram Middle Sheyenne SW: 380009
Count
0
1
2
3
4
0
200
400
600
Yearly EC (µS/cm)


Histogram Middle Sheyenne SW: 24750
Count
0.0
0.5
1.0
1.5
2.0
500
1000
1500
2000
Yearly EC (µS/cm)

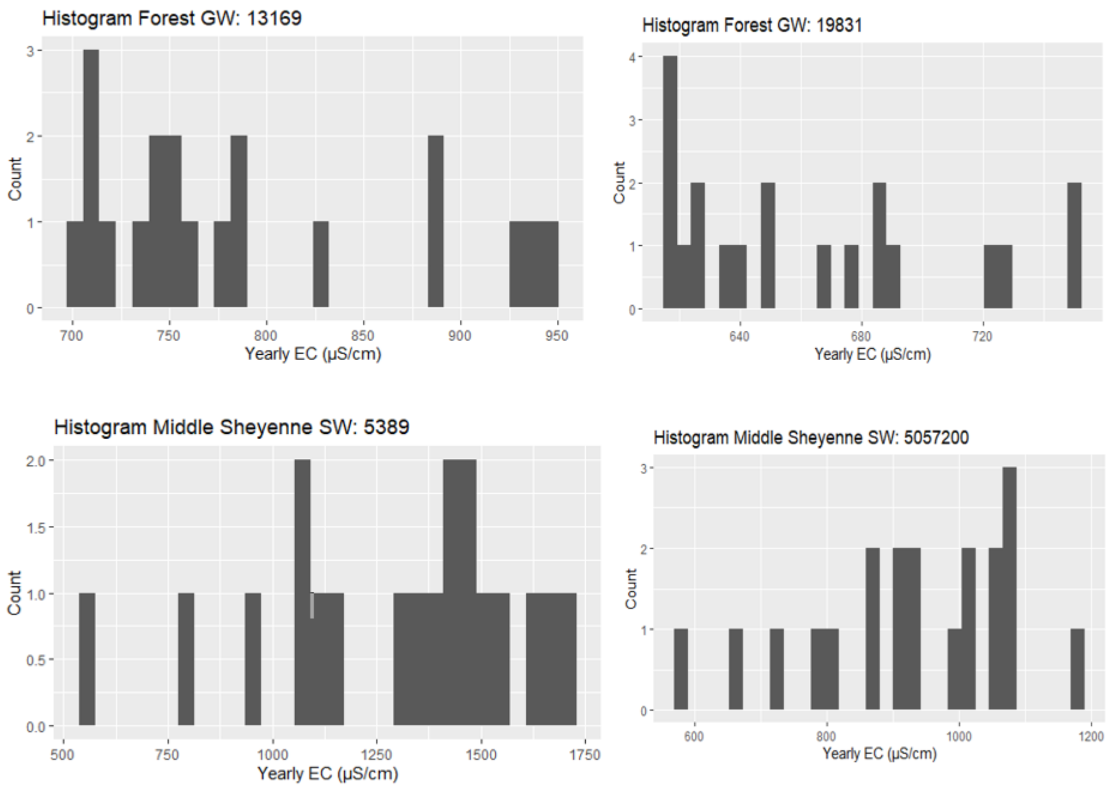


Figure A.4: Histograms used to evaluate distribution of all high temporal resolution sites for surface water and ground water in the Forest and Middle Sheyenne watersheds.

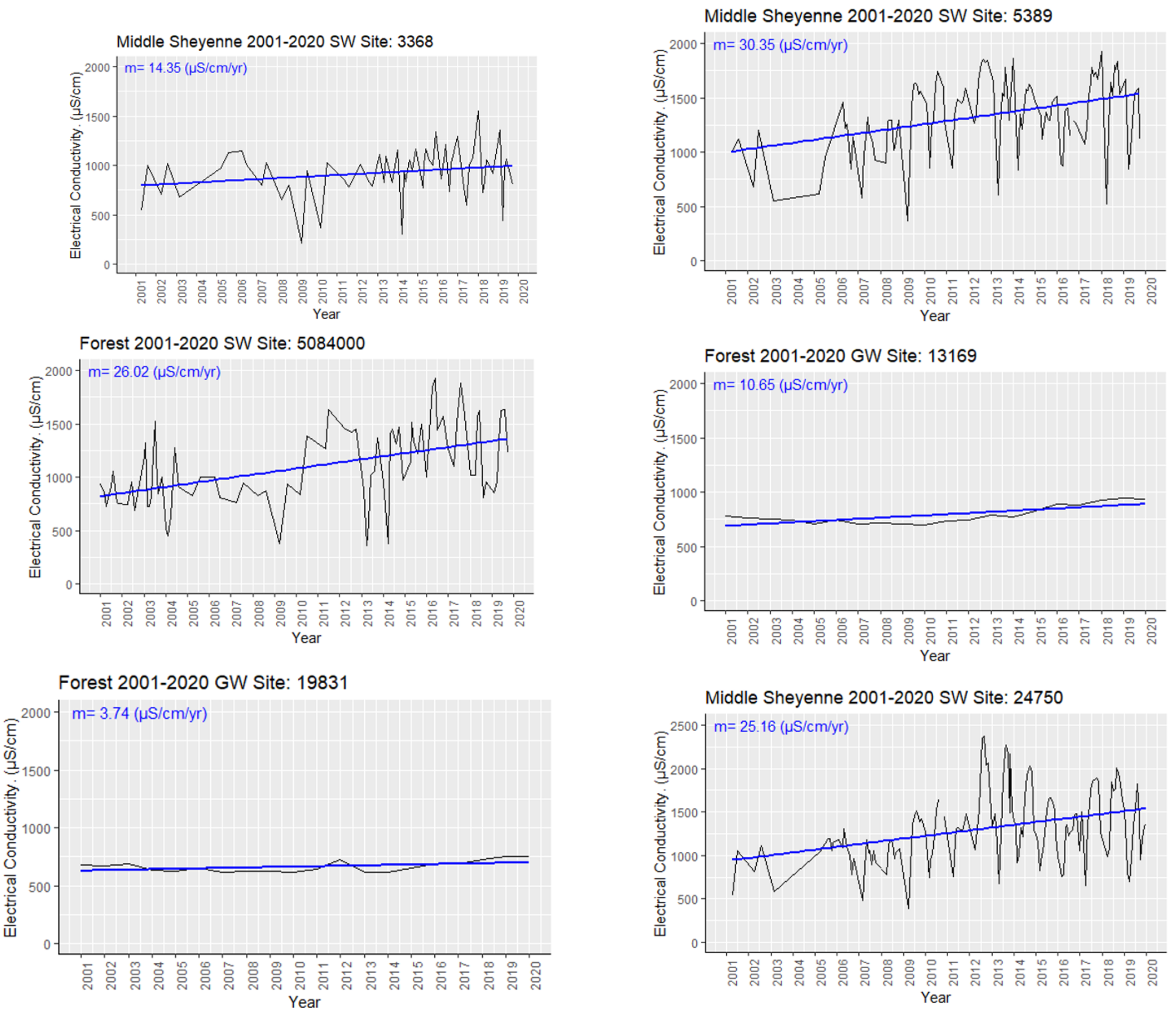


Figure A.5: Linear regression showing a line of best fit for the temporal salinity trends at high temporal resolution sites for both surface water and groundwater at the Middle Sheyenne and Forest watersheds.

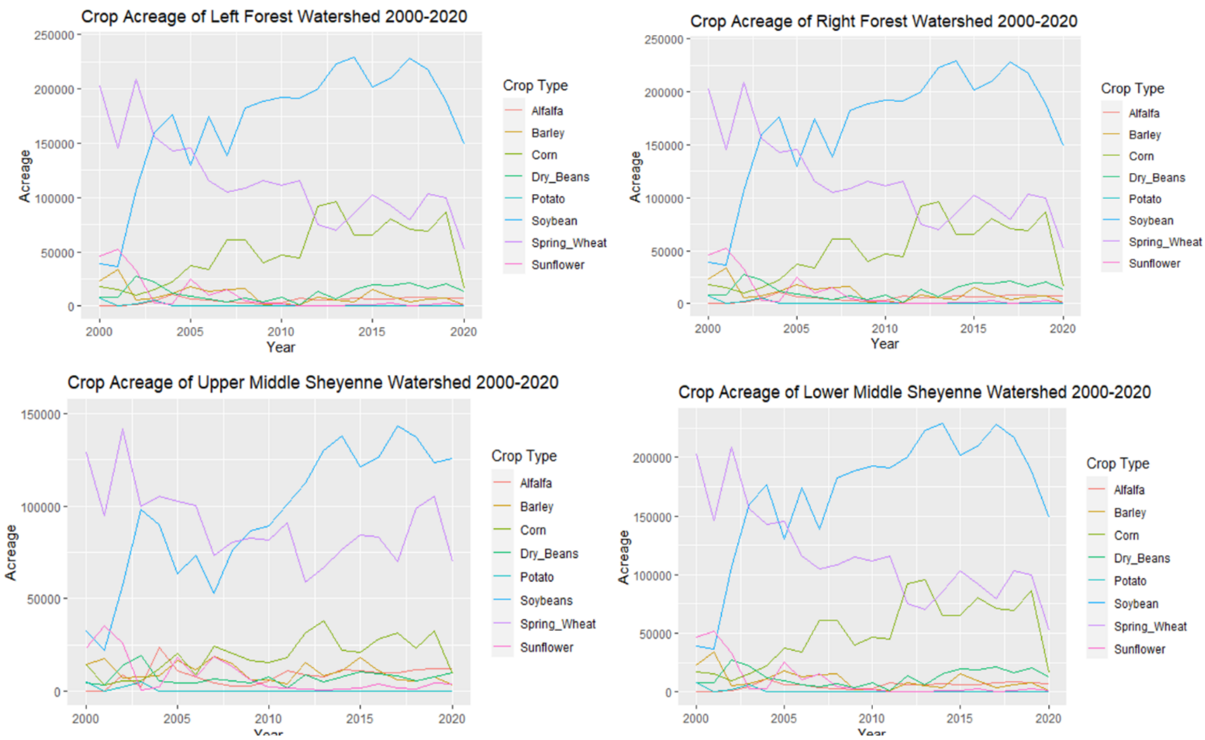


Figure A.6: Subbasin crop acreage for 2001-2020 of the left and right halves of the Forest watershed and the upper and lower halves of the Middle Sheyenne watershed.

Statement of originality of the MSc thesis

I declare that:

1. this is an original report, which is entirely my own work,
2. where I have made use of the ideas of other writers, I have acknowledged the source in all instances,
3. where I have used any diagram or visuals, I have acknowledged the source in all instances,
4. this report has not and will not be submitted elsewhere for academic assessment in any other academic course.

Student data:

Name: Andrew Cunningham

Registration number: 9523275

Date: 20/06/2022

Signature: Andrew Cunningham.