Using a Multi-Criteria Evaluation Model to Assess the Impact of Climate Change on the Suitability of Agricultural Lands to Grow Rainfed Maize, Soybean and Potatoes in Dufferin County

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Abstract

As global temperature and precipitation regimes continue to change as a result of climate change, the need to ensure high crop yield is of great importance. This can be achieved by identifying suitable land parcels for agricultural production. In this research, we develop unique Crop Suitability Indices (CSI) for potato, soybeans and maize in Dufferin County using a multi-criteria evaluation model to determine the most suitable land parcels for growing each of these crops. Based on current literature, it was determined that temperature, precipitation, slope, soil drainage and texture are criteria affecting crop production. Each criterion was ranked based on relative importance to crop production and the most suitable lands for agricultural production were identified. The CSI was subsequently applied to current and future (2050 and 2080) climate scenarios to analyze how climatic changes might impact the productivity of each crop. The results of this analysis show that overall land parcels will become more suitable for maize under both scenarios over the time period from both precipitation and temperatures becoming closer to optimal levels, soybean suitability decreases in the RCP4.5 scenario in 2050 but will stabilize by 2080 while increasing over the full time period of both scenarios, potato suitability will increase by 2050 in both scenarios but results in no significant change by 2080 due to its reliance on cooler temperatures for growth. Results of this analysis can be used by the county (as well as other parts of Southern Ontario) to see effects of climate change on agriculture in the region. As well as help as a 'stepping-stone' for future research.

Keywords: crop suitability index, parcels, multi-criteria evaluation, RCP 4.5, RCP 8.5

1. Introduction

1.1 Problem Context

The agricultural industry is one of, if not the most, important industries for human survival and prosperity. Over the next century, the UN is projecting that the global population will peak around 11 billion by 2100 (UN, 2019). This dramatic increase in population is creating a need to increase crop yields to ensure a food-secure population. To produce high yields of specific crops, certain environmental and climatic criteria must be met. Agro-ecological zoning (AEZ) is a process that groups similar areas of land dependent on climatic, topographic, soil and landform characteristics which are used to determine crop(s) most suitable to grow (Nabati et al. 2020), and also helps to identify the limiting factor(s) of crop growth in a certain area (Kamau et al. 2015).

Climate change is a huge problem facing farmers worldwide; with more extreme temperatures, changes in precipitation patterns, higher rates of disease and pest outbreaks, and a greater frequency of extreme weather events (Wiebe et al. 2019), all expected to cause significant changes to suitability of agricultural lands through changes in available water, soil composition, the number of growing days and the amount of evapotranspiration by crops (Jayathilaka et al. 2012). The importance of projecting climatic changes on current land suitability is clear. Although not exact, it will give governments, farmers, and scientists crucial information about farmland that will face the most stressors in the changing climate. This helps to not only determine which crops to grow on a certain area, but also management strategies to implement.

Effects of climate change on agriculture are not felt the same across the globe; areas close to the equator will experience harsher effects with great losses in crop productivity from very high temperature increases and decreasing water availability (Smith et al. 2013). However, more temperate climates, like in Southern Ontario may experience higher crop productivity through longer growing periods. Conversely, climate change in these regions could contribute to adverse effects, such as the increased potential for pest outbreaks and the possibility of less available water (Smith et al. 2013). Dufferin county in Southern Ontario is in the process of creating a climate action plan and would like to know the effect of a changing climate on agricultural lands in the area. Most literature on Geographic Information Systems (GIS) AEZ analysis with climate change projections are in areas of lower latitudes (Hamzeh et al. 2014; Jayathilaka et al. 2012; Kamau et al. 2015; Nabati et al. 2020), with few articles focusing on temperate climates (Daccache et al. 2012; Zhang et al. 2015). Canadian AEZ studies have not considered climate change, instead focused solely on current climate (Halder, 2013). This project will look at AEZ and how it is affected by climate change in Southern Ontario.

The use of GIS is crucial for AEZ and projecting how it may change over time. Factors that affect the suitability for certain crops to grow occur non-uniformly even at very small spatial scales, including soil composition, temperature and precipitation (Hodson & White, 2010; Jayathilaka et al. 2012). This approach also requires multiple large datasets which GIS are powerful enough to analyze and project with speed and flexibility (Mazahreh et al., 2019). Therefore, the use of GIS is necessary to effectively model crop suitability and project future changes.

1.2 Research Purpose

The purpose of this research is to develop a CSI for Dufferin County using climatic, environmental, and topographic variables which play important roles in ensuring high crop yields and projecting future climatic changes to determine areas most suitable for future crop growth.

1.3 Objectives

1. Identify criteria and constraints affecting the suitability of land parcels to grow specific crops in Dufferin County.
2. Develop a multi-criteria evaluation to produce a crop growth suitability raster for each crop (potatoes, maize and soybean).
3. Project climate scenarios to each raster to predict changes in the suitability of land parcels to grow specific crops in the study area.
4. Perform change detection analysis to determine impact of climate scenarios on crop growth suitability.
5. Assess strengths and limitations of the approach used.

2. Study Area

Southern Ontario is one of the fastest growing areas in the World with projections seeing growth of over 25% in most of the region by 2046 (Ontario Ministry of Finance, 2020). Due to this, agricultural land must be able to increase production to feed the growing population. Agriculture is one of the biggest industries in Dufferin County, according to a 2016 census by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) having more than 150,000 acres of farmland (almost half of its total area) (Mailvaganam, 2017). With Dufferin being a large agricultural community, the county needs these crop suitability projections to be prepared for a changing climate and increased population of Southern Ontario while also making an honest living that all farmers desire. The top 3 crops grown in the area are potatoes, soybeans and maize. Therefore, we will be basing our study around them (Dufferin Federation of Agriculture, 2017).

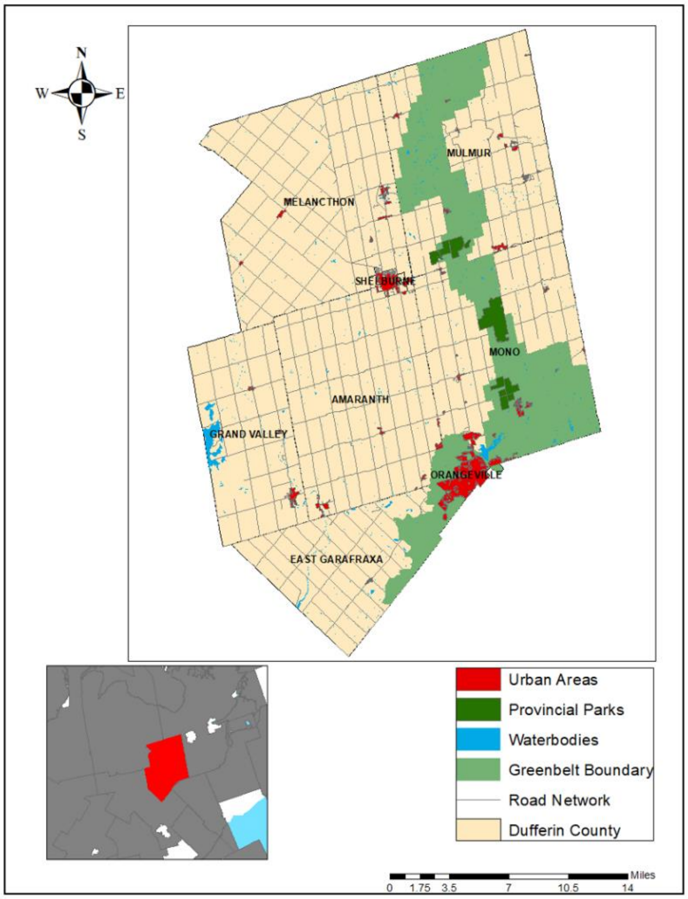


Figure 1: Detailed view of Dufferin County including relevant variables such as roads, waterbodies, urban areas and conservation areas

3. Research Approach

Objective 1: Identify criteria and constraints affecting the suitability of land parcels to grow specific crops in Dufferin County.

The first step to determine land suitability was to identify characteristics that increase or decrease suitability of a land parcel with regards to being able to grow a specific crop. Factors relevant to this analysis include climatic variables (temperature and precipitation) and environmental variables (topography/slope, soil texture and drainage) (U.S. Department of the Interior, 2014). Constraints affecting land suitability include waterbodies, urban and conservation areas.

Temperature

Increases in global temperatures could result in physical damages, physiological disruptions and biochemical changes to crops which could lead to declines in production (Fahad et al., 2017). Each crop has an optimal average temperature range during a growing season, with suitability worsening the further away the actual temperature is.

Precipitation

Changes in global hydrological regimes will disrupt average seasonal precipitation. These disruptions could cause a decrease in precipitation resulting in low soil moisture or increase the frequency of heavy precipitation leading to flooding and disease infestation (Neenu et al., 2013). Like temperature, there is an optimal total precipitation range during a growing season for each crop type.

Topography (Slope)

Topography of agricultural land is important for crop yields because it affects surface runoff and drainage, flow accumulation, and nutrient and pesticide leakage (Kumhálová et al., 2008). Steep slopes are less favorable for crop growth because they are subject to erosion and nutrient leaching. Flat slopes are also susceptible to floods and flow accumulation which results in poor soil drainage (U.S. Department of the Interior, 2014).

Soil Texture and Drainage

Soils are a fundamental part of agriculture, with researchers considering various soil characteristics as key components of AEZ (Abd-Elmabod et al., 2017; Mazareh et al., 2019; Taghizadeh-Mehrjardi et al., 2020). Soil texture influences drainage, water holding capacity, aeration, and susceptibility to erosion (Gómez-Guerrero & Doane, 2018; Upadhyay & Raghubanshi, 2020). Soils without adequate drainage will only be well suited to water-loving crops and crops with shallow rooting systems. Drainage also directly influences aeration of soils. Without proper aeration, most crops will 'choke' and die (Magdoff & van Es, 2020).

Constraints (Waterbodies, Urban and Conservation Areas)

Existing waterbodies and lands that have been urbanized or are protected by a conservation area are constraints to our model. It is highly unlikely that Dufferin will convert developed land into cropland in the future, and we are assuming that similar conditions apply to land within conservation areas. Similarly, water bodies cannot have crops growing on them.

Objective 2: Develop a multi-criteria evaluation to produce a crop growth suitability raster for potatoes, maize and soybean.

MCE was chosen for this problem as it is widely considered as the best method to determine AEZ (Radocaj et al. 2020; Nabati et al. 2020). The ability of MCEs to standardize multiple factors and weight them against each other through a pairwise comparison allows us to determine which factors will affect the suitability of a certain crop the most. The first step was to clip data to county limits, rasterize any vector data inputs and resample all data to the same spatial scale (30m spatial resolution). We then created binary rasters for constraints with values of 1 (suitable) or 0 (unsuitable). Equations 1 and 2 were used to standardize each criterion depending on its effect on crop suitability (Full process found in figure 5).

Table 1: Criteria and constraints for the MCE

Variable (Unit)	Criteria or Constraint	Beneficial or Cost	Data Source
Average Temperature in Growing Season (°C)	Criteria	Beneficial for maize and soybean; Cost for potato	Climate Canada, 2020
Total Precipitation in Growing Season (mm)	Criteria	Beneficial	Climate Canada, 2020
Slope (%)	Criteria	See Tables 2	Ontario Ministry of Natural Resources and Forestry - Provincial Mapping Unit
Soil Texture (Categorical)	Criteria	See Tables 3	Ontario Ministry of Agriculture, Food and Rural Affairs
Soil Drainage (Categorical)	Criteria (Very Poor drainage is a constraint for potato)	See Tables 4	Ontario Ministry of Agriculture, Food and Rural Affairs
Waterbodies	Constraint	N/A	Ontario Ministry of Natural Resources and Forestry - Provincial Mapping Unit
Urban Areas	Constraint	N/A	Ontario Ministry of Natural Resources and Forestry
Conservation Areas/Provincial Parks	Constraint	N/A	Ontario Ministry of Municipal Affairs and Housing

Standardization and Constraint Mapping

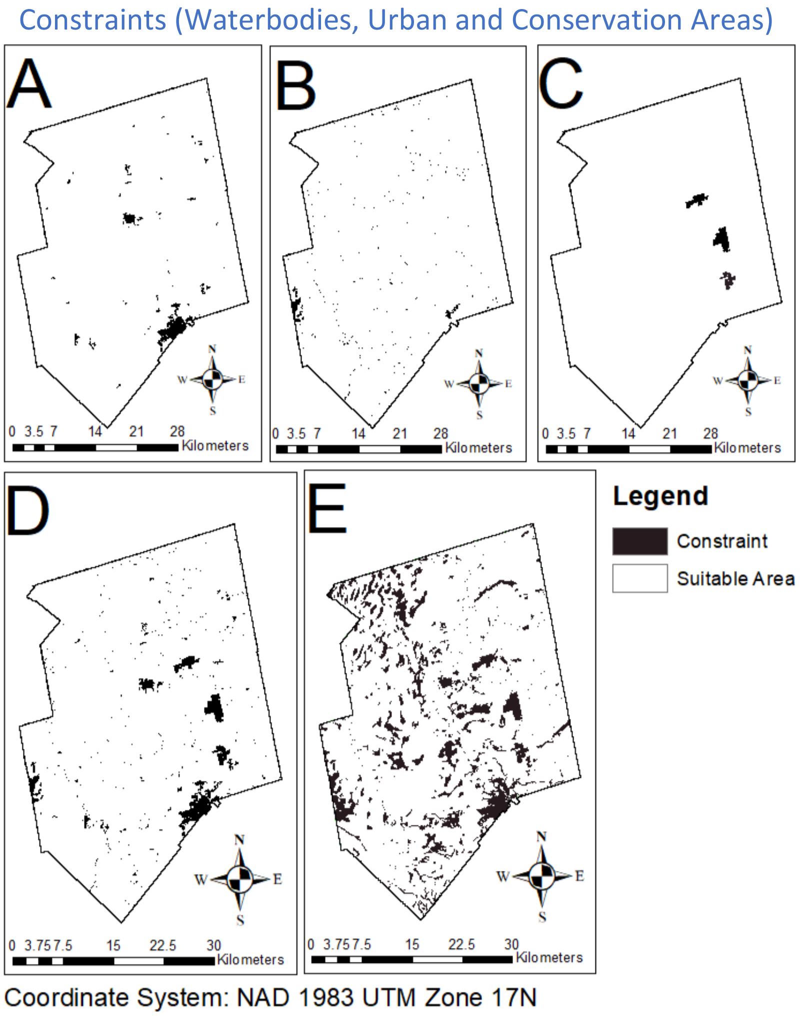


Figure 2: Constraint maps; (A) built-up area, (B) waterbodies, (C) provincial parks/conservation areas, (D) combined constraint map for maize and soybean, and (E) added very poor drainage areas for combined constraint map for potatoes

Equation 1: Beneficial factor equation used to standardize certain criteria:

$$Beneficial\ Criteria: X'_{ij} = 100\left(\frac{X_{ij} - X_{min}}{X_{max} - X_{min}}\right)$$

Equation 2: Cost factor equation used to standardize certain criteria:

$$Cost\ Criteria: X'_{ij} = 100(1 - \left(\frac{X_{ij} - X_{min}}{X_{max} - X_{min}}\right))$$

Where X'_{ij} is the standardized criteria, ranging from 0-100, X_{ij} is the original value of the criteria, X_{max} is the maximum value of the criteria while X_{min} is the minimum value of the criteria.

Slope

Slope was derived from a 30m DEM to complete the following, standardized maps can be found in Appendix C.

Table 2: Slope suitability for maize, potato and soybean; data reclassified based on the value within parentheses

Crop Type	Highly Suitable (100)				Least Suitable (0)	Data Source
Maize	0-2%	2-6% (75)	6-12% (50)	12-16% (25)	>16%	Tashayo et al. 2020
Potato	0-5%	5-7% (66)	-	7-9% (33)	>9%	GNB Canada (n.d.)
Soybean	0-3%	3-8% (75)	8-15% (50)	15-30% (25)	>30%	Kumar et al. (2017)

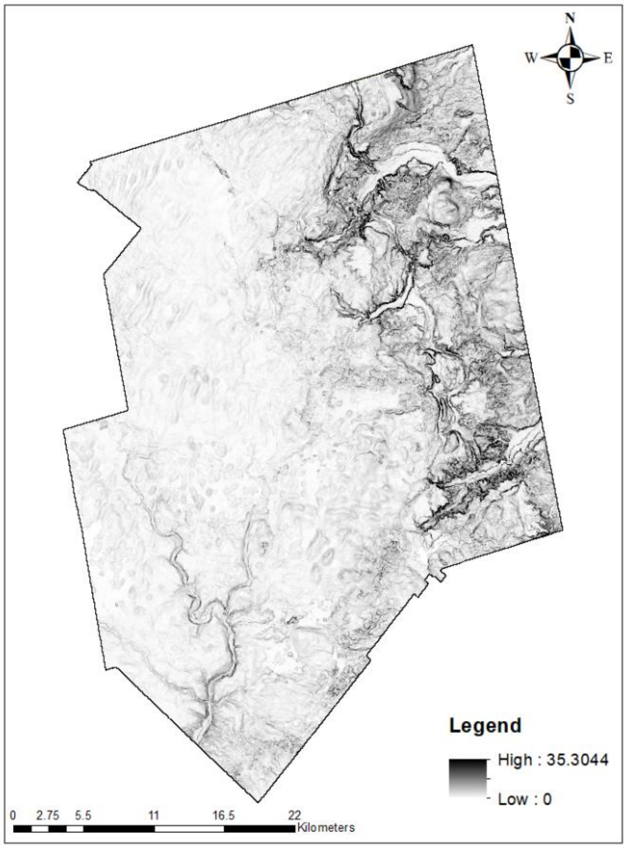


Figure 3: Map showing slope (%) of Dufferin County

Soil Texture and Drainage

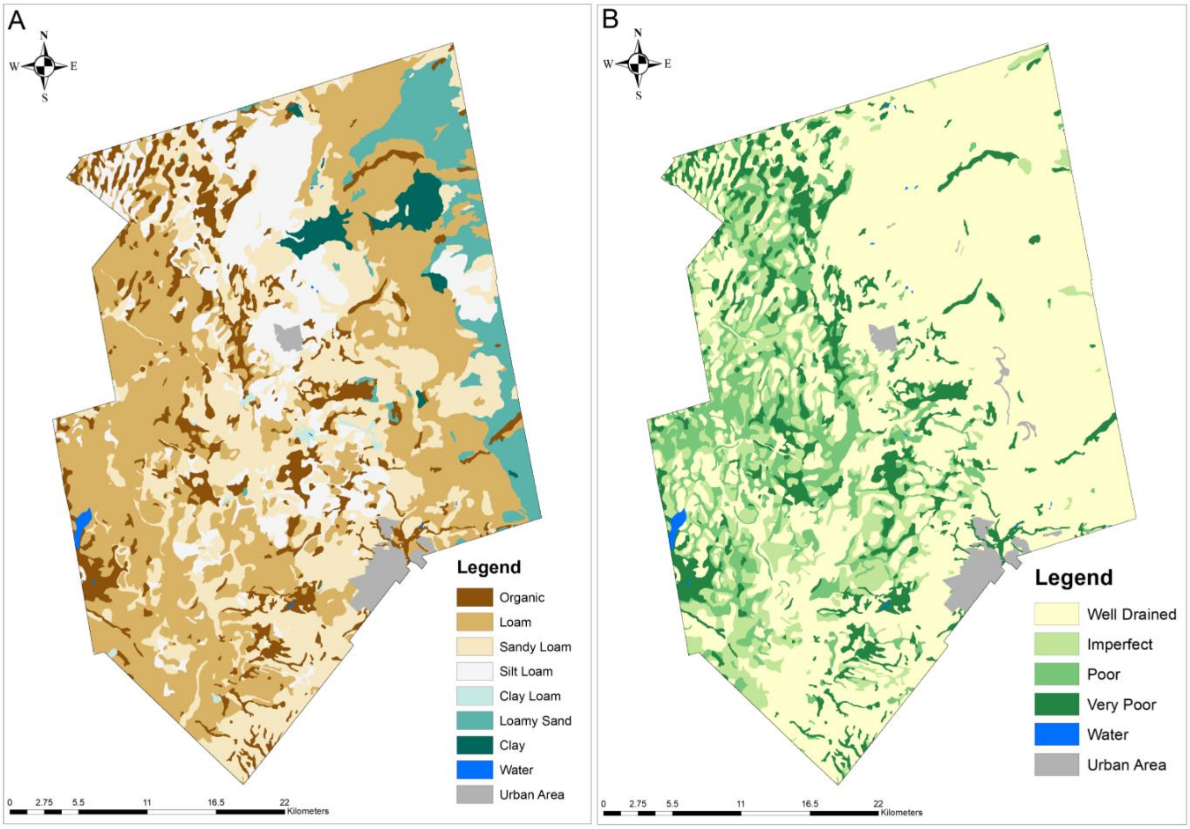
The Ontario Soil Survey Complex contains both variables at the field level. Both texture and drainage are categorical data and were standardized based on planting guidelines for each crop. Tables 3 and 4 categorize soil textures and drainage respectively on the suitability for each crop based on previous studies and crop guidelines. Standardized maps can be found in Appendix C.

Table 3: Soil texture suitability for maize, potato and soybean; data reclassified based on the value within parentheses

Crop	Most Suitable (100)	Very Suitable (75)	Moderately Suitable (50)	Barely Suitable (25)	Least Suitable (0)	Data Source
Maize	Organic	Loam, clay loam, sandy clay, clay	Sandy loam, sandy clay loam	Silty loam, silty clay loam, loamy sand	Silty clay, sand, silt	Tashayo et al. 2020
Potato	Organic	Loam, sandy loam, sandy clay loam, silt loam	Clay loam, silty clay loam, loamy sand	Silty clay, sandy clay	Clay, sand, silt	GNB Canada (n.d.)
Soybean	Organic	Loam, Clay loam	Silt loam, sandy loam, silty clay loam	Sandy clay, silty clay, sandy clay loam	Clay, sand, silt, Loamy sand	Radocaj, et al. 2020

Table 4: Soil drainage suitability for maize, potato, and soybean; data was reclassified based on value within parentheses

Crop Type	Highly Suitable	Moderately Suitable	Slightly Suitable	Barely Suitable	Not Suitable	Data Source(s)
Maize and Soybean	Well Drained (100)	Imperfect Drainage (66)	Poor Drainage (33)	Very Poor Drainage (0)		Makoi & Mmbaga (2020)
Potato	Well Drained (100)	Imperfect Drainage (50)	Poor Drainage (0)		Very Poor Drainage (Constraint)	GNB Canada (n.d.)



Coordinate System: NAD 1983 UTM Zone 17N

Figure 4: Maps showing (A) soil texture and (B) soil drainage classes of Dufferin county

Temperature and Precipitation Raster Creation

Historical temperature and precipitation data were collected using weather station data from the Government of Canada. Data was collected between 1981-2010 with average monthly temperatures and precipitation, along with coordinates of each station which can be found in Appendix A.

Monthly average data was collected from each station and added to a new table which was imported into ArcMap as point data. An Ordinary Kriging interpolation method was used for each month with temperature and precipitation respectively to create continuous monthly rasters of each variable. Raster calculator was used to combine months (depending on growing season of each crop) making average temperature and total precipitation over each crop's growing season continuously over the study area.

Standardization of climate variables was completed on a linear scale across all scenarios and time periods. For each crop maximum and minimum values of total precipitation and average temperature over both scenarios and current climate for a proper comparison between time periods and scenarios. Equations 1 and 2 were used to standardize each raster; Potato temperature was the only cost criteria in this set of data. Standardized rasters can be found in Appendix C along with maximum and minimum values.

Table 5: Growing seasons and optimal values of climate variables during growing season of each crop

Crop	Optimal Total Precipitation (mm)	Optimal Average Temperature (°C)	Growing Season	Data Sources
Maize	500 - 800	22 - 26	Start of May – Start of October (5 months)	Tashayo et al. (2020) Brouwer & Heibloem (1986) OMAFRA (2017) OMAFRA (2021)
Soybean	450 - 700	20 - 24	Start of June – End of September (4 months)	He et al. (2014) Brouwer & Heibloem (1986) OMAFRA (2017) OMAFRA (2021)
Potato	500 - 70	<18	Start of April – Start of July (4 months)	GNB Canada (n.d.) Brouwer & Heibloem (1986) OMAFRA (2021) Ontario Potato Board (2021)

Determining Weights for MCE Analysis

Weights were determined to indicate the importance of each criterion to suitability of crops to grow. They were derived using an Analytical Hierarchy Process (AHP) proposed by Saaty and Vargas (1980) using the following scale (Full process found in Appendix B):

Table 6: 9-point rating scale showing relative level of importance

0.111	0.143	0.2	0.333	1	3	5	7	9
Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very Strongly	Extremely
Less important				Equally				More important

MCE Equation

With all weights assigned, suitability raster was completed with the creation of an MCE algorithm. This equation uses the standardized factors multiplied by the weight of the specific criterion. All values were then summed and multiplied by each constraint to develop a suitability raster (Eastman, 2005).

$$Crop\ Suitability = FM\ (C_1W_1 + C_2W_2 + C_3W_3 + C_4W_4 + C_5W_5)$$

Where, FM = Final Map Constraint, C = Criteria, and W = Assigned Weight

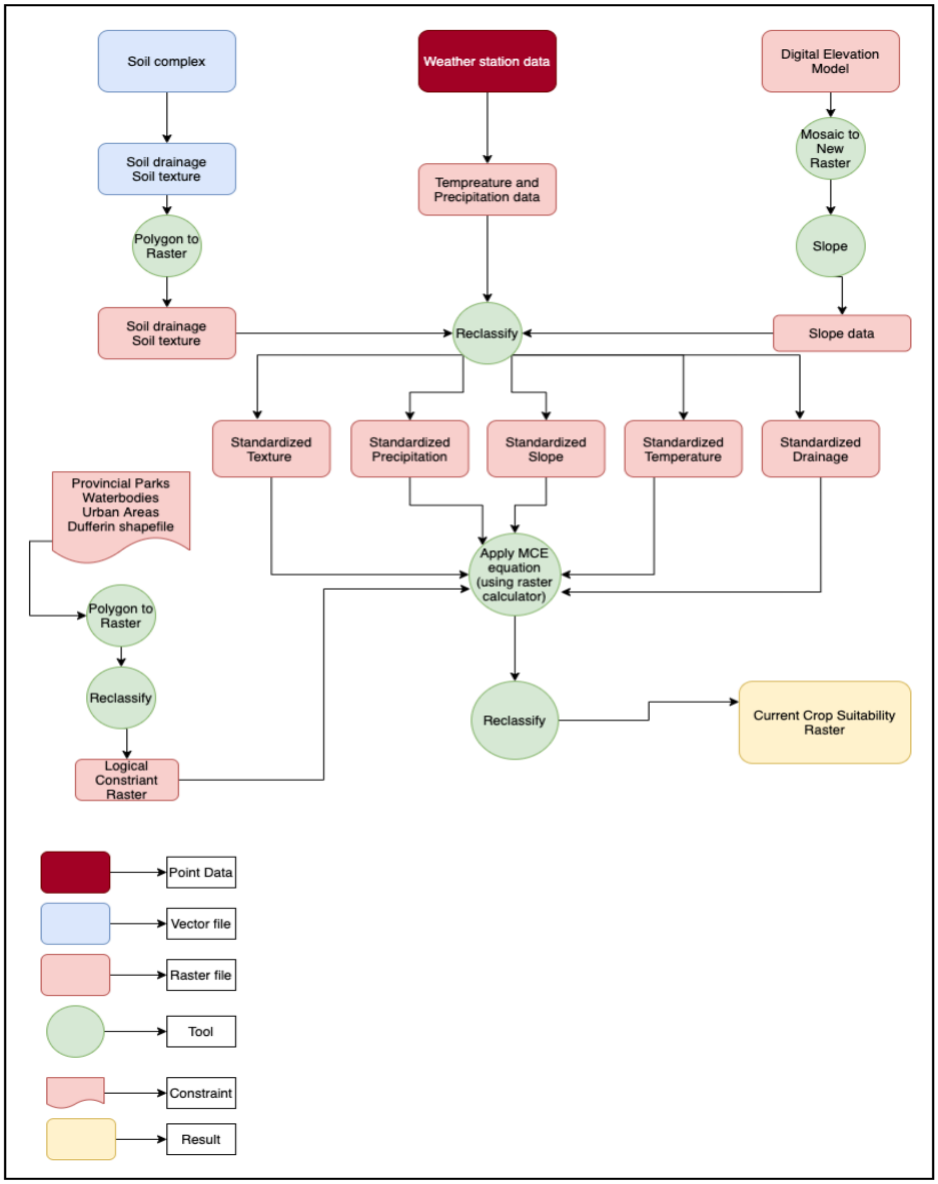


Figure 5: Flowchart summary for the creation of the Crop Growth Suitability raster. Refer to Appendix B for detailed flowcharts

Objective 3: Project climate scenarios to each raster to predict changes in the suitability of land parcels to grow specific crops in the study area.

Current climate variables were changed to projected variables where applicable for RCP4.5 and RCP8.5 projections. These 2 scenarios were chosen because they vary in the way climate change is impacted. RCP4.5 is described as an intermediate-emission scenario, where carbon emissions peak in 2040 but begin to decline while RCP8.5 is considered the worst-case scenario (IPCC, 2019; San José et al., 2016). We used these scenarios to create projected suitability rasters for each scenario and crop. The new projected rasters are for the years 2050 and 2080 for each scenario. Projected climate rasters were created using the same method as historical data. Climate Canada (2020) allowed us to choose point data and project at different RCP scenarios.

Objective 4: Perform change detection analysis to determine impact of climate scenarios on crop growth suitability.

To compare projected suitability rasters with the current suitability rasters, we used the raster calculator tool to subtract the two rasters. The result of this was a raster showing the differences in suitability between time periods with positive values showing greater suitability in the future while negative values indicated a loss in suitability (can be seen in Figure 6).

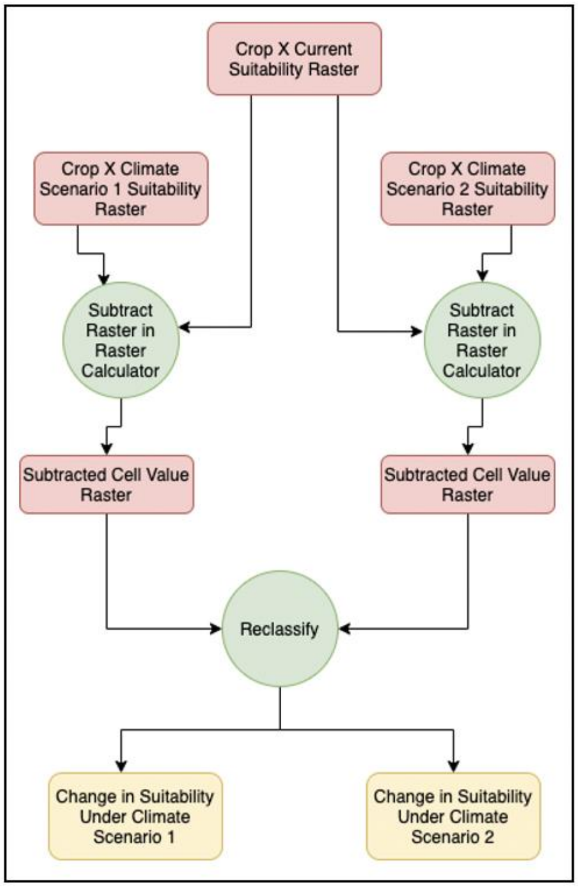


Figure 6: Flowchart for performing a change detection analysis for projected crop suitability and current crop suitability

4. Results

4.1 MCE Analysis

Generation of continuous suitability rasters were created for each crop in each time period discussed as well as in both climate projections. Each raster was classified based on suitability score into 5 discrete groups from most suitable to least suitable; S1 (100 – 80), S2 (80 – 70), S3 (70 - 60), S4 (60 – 50), and N (50 – 0) which can be seen below.

Maize

Looking at the suitability of maize (Figure 7), the county generally becomes more suitable over time where in both scenarios' areas with a suitability of 50 or under become minimal compared to the current area which is shown to be about half with that score. In 2080 both scenarios have areas on the Eastern side with S2 land and RCP8.5 even becoming very suitable.

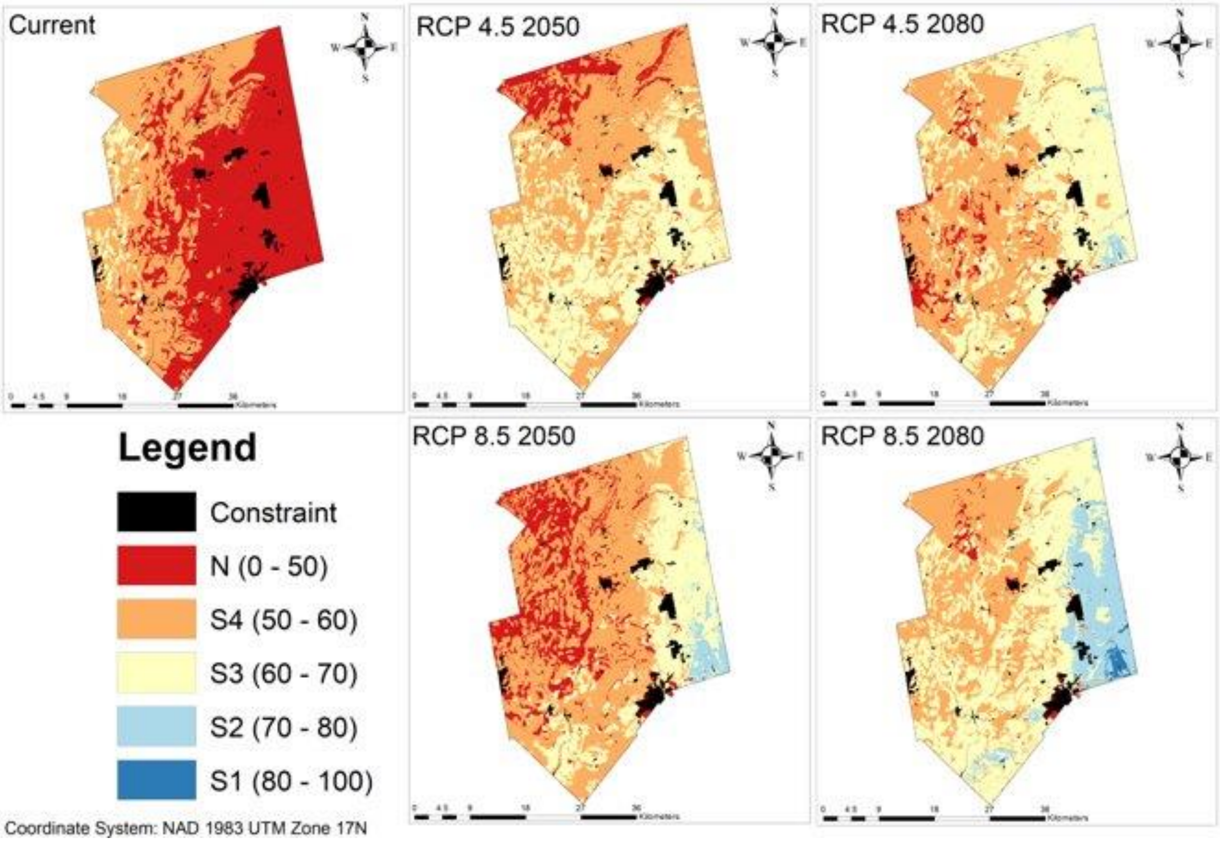


Figure 7: Final maize MCE analysis grouped into 5 classes

Table 7: Amount of each suitability class in each analysis for maize in hectares and percentage of the total area of Dufferin County

Year and Scenario	2020	RCP 4.5 2050	RCP 4.5 2080	RCP 8.5 2050	RCP 8.5 2080
S1	0	0	0	0	40.43 ha (0.01%)
S2	0	0	73.42 ha (1.47%)	148.14 ha (2.96%)	694.87 ha (13.88%)
S3	209.00 ha (4.17%)	1999.09 ha (39.92%)	2258.94 ha (45.11%)	1209.57 ha (24.15%)	2319.64 ha (46.32%)
S4	1962.35 ha (39.19%)	2433.65 ha (48.60%)	2236.71 ha (44.67%)	2576.26 ha (51.45%)	1704.14 ha (34.03%)
N	2657.04 ha (53.06%)	395.59 (7.90%)	259.31 ha (5.18%)	894.42 ha (17.86%)	69.31 ha (1.38%)

Soybean

Soybean is shown to become less suitable by a high margin from current times to 2050 in the RCP4.5 scenario however by 2080 the trend of the county overall becoming more suitable can be seen in Figure 8. RCP8.5 in 2050 has the highest suitability overall, most likely due to an increase in precipitation during the time period when compared to RCP4.5 and RCP8.5 in 2080.

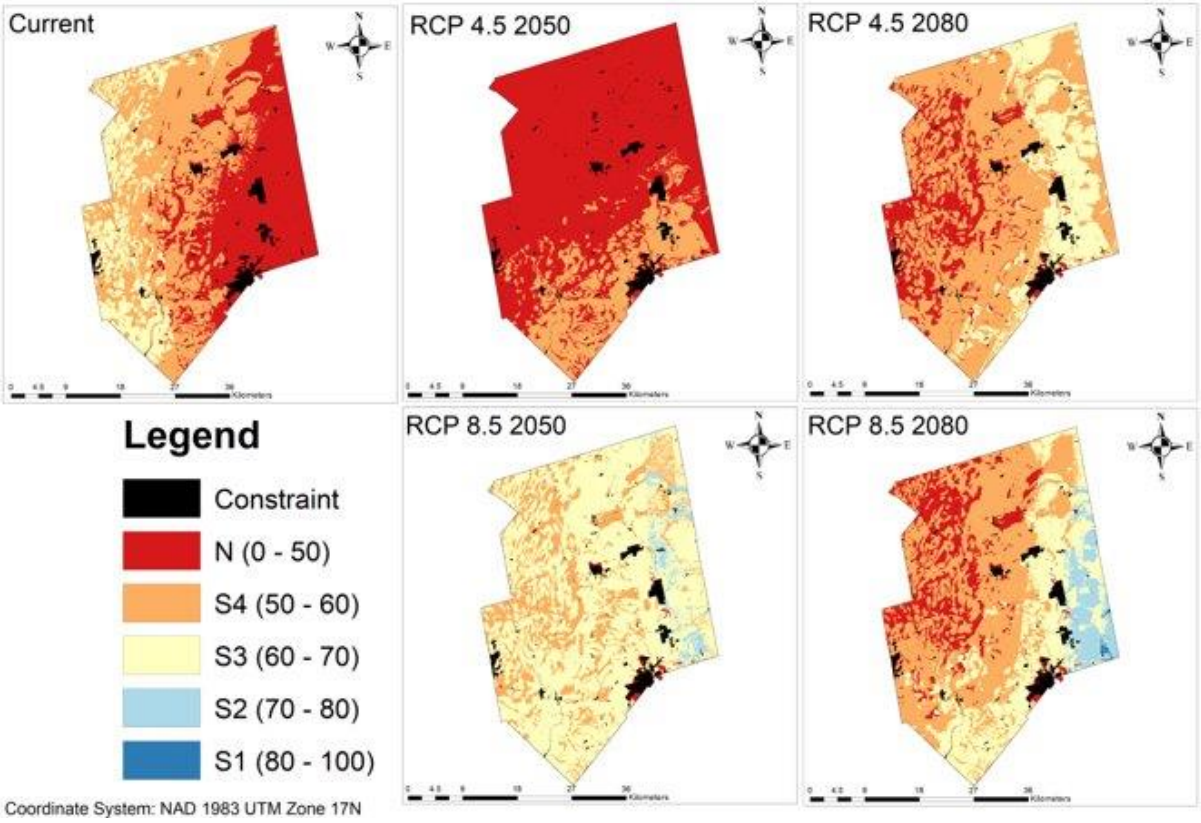


Figure 8: Final soybean MCE analysis grouped into 5 classes

Table 8: Amount of each suitability class in each analysis for soybean in hectares and percentage of the total area of Dufferin County

Year and Scenario	2020	RCP 4.5 2050	RCP 4.5 2080	RCP 8.5 2050	RCP 8.5 2080
S1	0	0	0	0	9.69 ha (0.001%)
S2	0	0	0	149.57 ha (2.99%)	340.84 ha (6.81%)
S3	762.18 ha (35.91%)	0	1055.64 (21.08%)	3464.33 ha (69.18%)	1297.48 ha (25.91%)
S4	2267.76 ha (45.29%)	1055.02 ha (21.07%)	2888.72 ha (57.69%)	1184.85 ha (23.66%)	2410.21 ha (48.13%)
N	1798.45 ha (35.91%)	3773.37 ha (75.35%)	883.89 ha (17.65%)	29.63 ha (0.01%)	770.17 ha (15.38%)

Potato

Figure 9 illustrates suitability for potato production over time with both scenarios having a high suitability in 2050 while by 2080, suitability drops across the whole county. This is due to an increase in precipitation during 2050 however, by 2080 temperature rise becomes too high and causes a decrease in suitability as it prefers cooler climates. A change in growing season to earlier planting dates and harvest times may be needed by 2050.

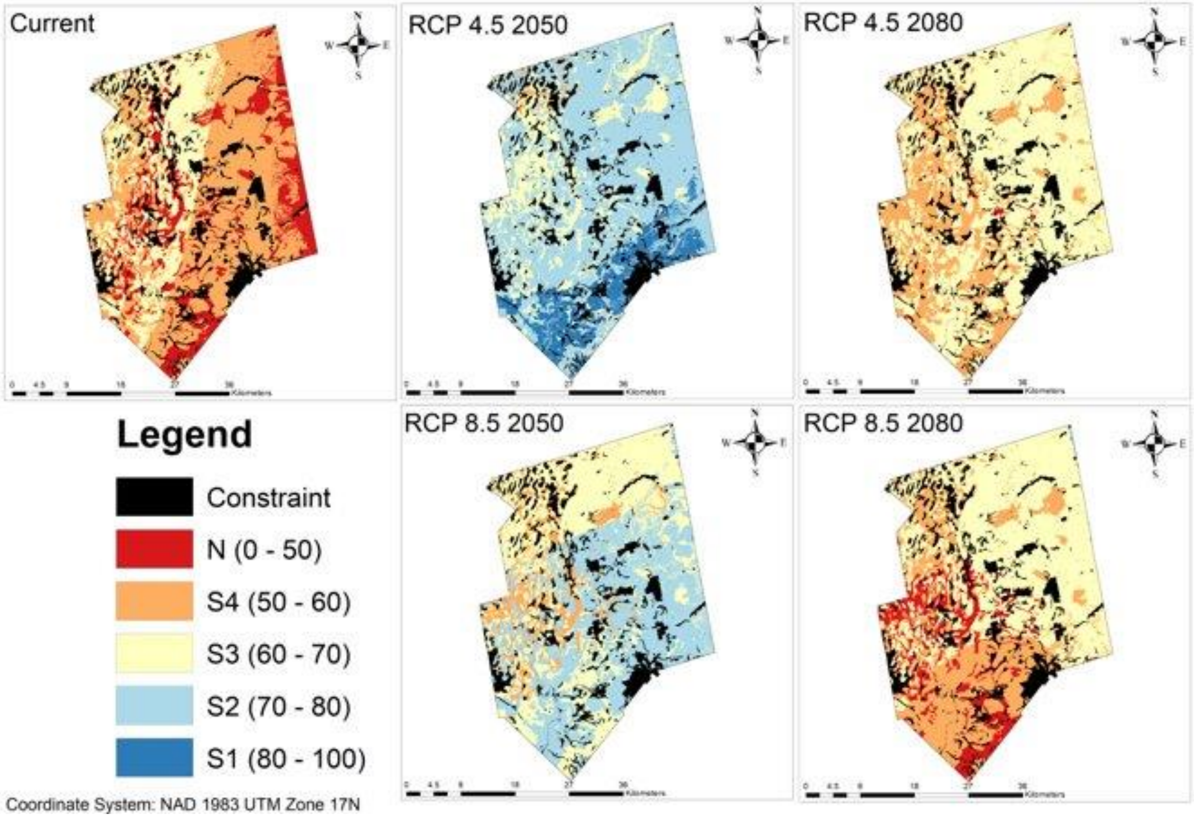


Figure 9: Final potato MCE analysis grouped into 5 classes

Table 9: Amount of each suitability class in each analysis for potato in hectares and percentage of the total area of Dufferin County

Year and Scenario	2020	RCP 4.5 2050	RCP 4.5 2080	RCP 8.5 2050	RCP 8.5 2080
S1	0	528.36 ha (10.93%)	0	0	0
S2	0	2755.17 ha (56.99%)	0	1868.29 ha (38.65%)	4.04 ha (0.001%)
S3	1061.99 ha (21.97%)	835.99 ha (17.29%)	2830.09 ha (58.54%)	1792.98 ha (37.09%)	2284.49 ha (47.26%)
S4	2264.45 ha (46.84%)	50.72 ha (1.05%)	1320.73 ha (27.32%)	508.37 ha (10.52%)	1371.46 ha (28.37%)
N	843.83 ha (17.46%)	0	19.45 ha (0.01%)	0	510.29 ha (10.56%)

4.2 Change Detection

Maize

According to our analysis, maize will see a general increase in suitability over 2020 – 2080 with the possibility of a slight decrease on the Western side of Dufferin (Figure 10). The biggest change in suitability will be seen on the Eastern side between the years of 2020 – 2050 with only slight changes between 2050 and 2080.

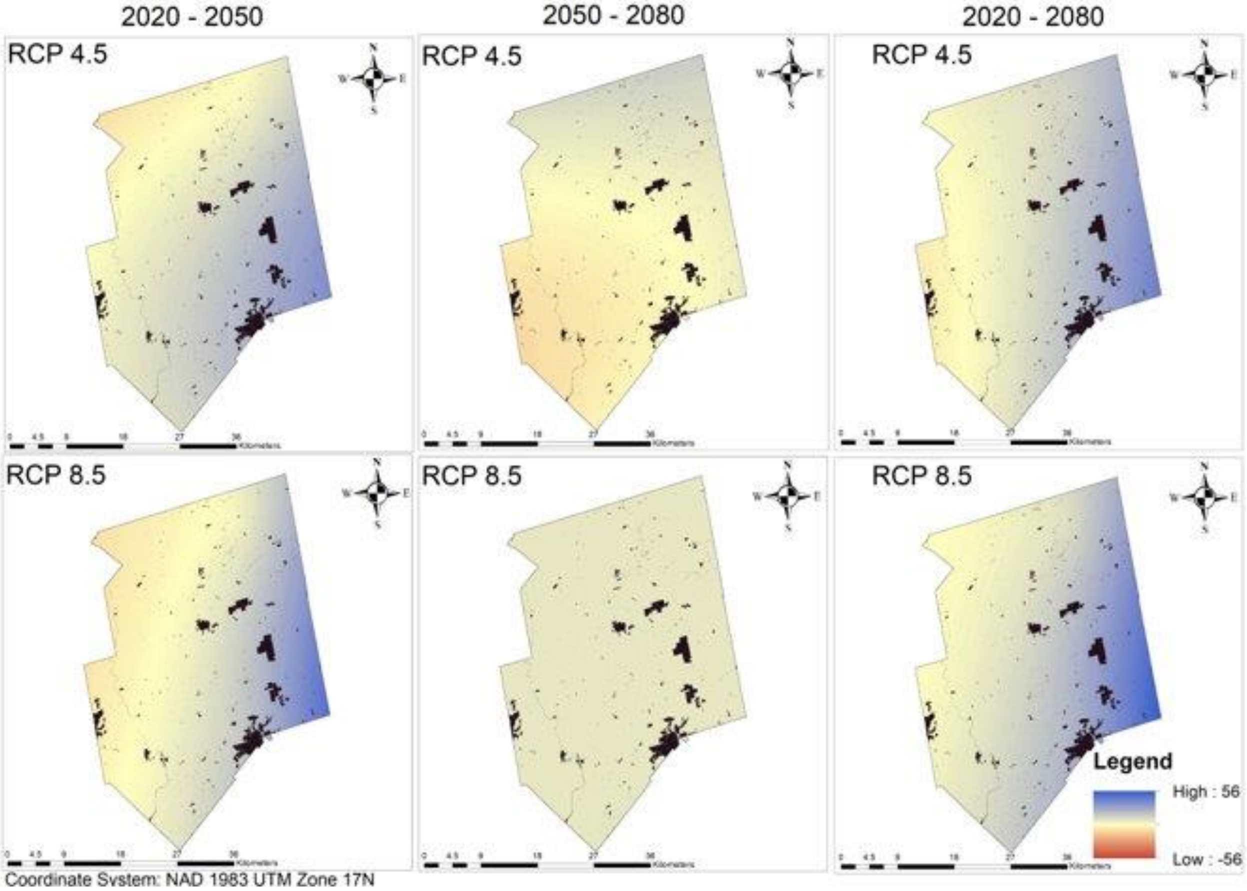


Figure 10: Continuous change detection maps for maize between 2020 – 2050, 2050 – 2080 and 2020 – 2080

Table 10: Mean percent change in suitability for maize production over each time period and scenario

Scenario and Time Period	Mean Change (% Suitability)
RCP 4.5 2020 - 2050	10.28
RCP 4.5 2050 - 2080	0.70
RCP 4.5 2020 - 2080	10.98
RCP 8.5 2020 - 2050	7.91
RCP 8.5 2050 - 2080	6.44
RCP 8.5 2020 - 2080	14.35

Soybean

Figure 11 shows soybean could see a high decrease in suitability in the Northeast area of the county due to a drop in rainfall over the growing season (seen between 2020 and 2050 of RCP4.5, while a slight decrease in suitability can be seen in RCP 8.5 between 2050 and 2080). Overall, the Eastern side will see a net positive increase while the Western area may see a small decrease in suitability.

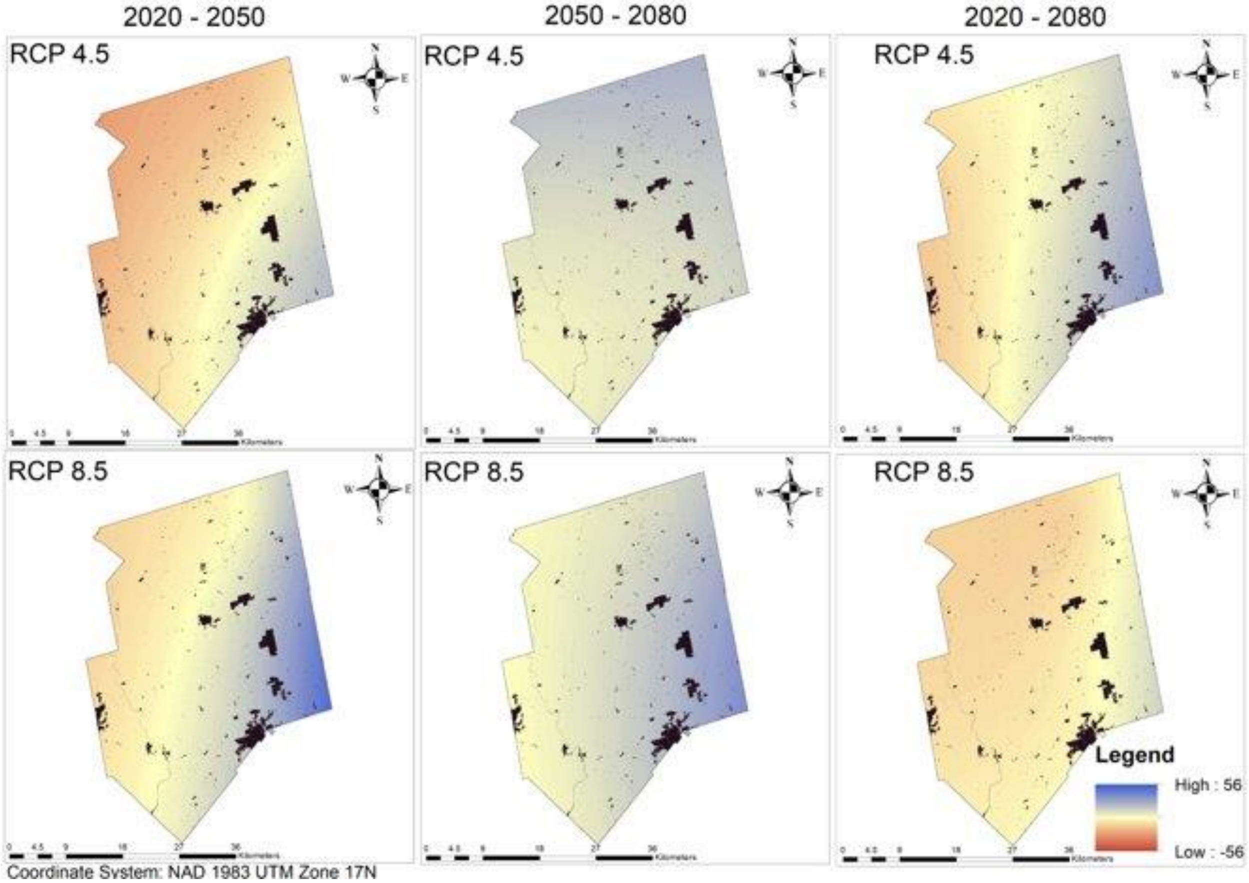


Figure 11: Continuous change detection maps for soybean between 2020 – 2050, 2050 – 2080 and 2020 – 2080

Table 11: Mean percent change in suitability for soybean production over each time period and scenario

Scenario and Time Period	Mean Change (% Suitability)
RCP 4.5 2020 - 2050	-7.43
RCP 4.5 2050 - 2080	11.04
RCP 4.5 2020 - 2080	3.61
RCP 8.5 2020 - 2050	11.55
RCP 8.5 2050 - 2080	-5.99
RCP 8.5 2020 - 2080	5.56

Potato

As seen in the MCE analysis, potatoes will see a high increase in suitability between 2020 and 2050 however an almost equal decrease will be seen between 2050 and 2080 in both scenarios resulting in almost no change between 2020 and 2080.

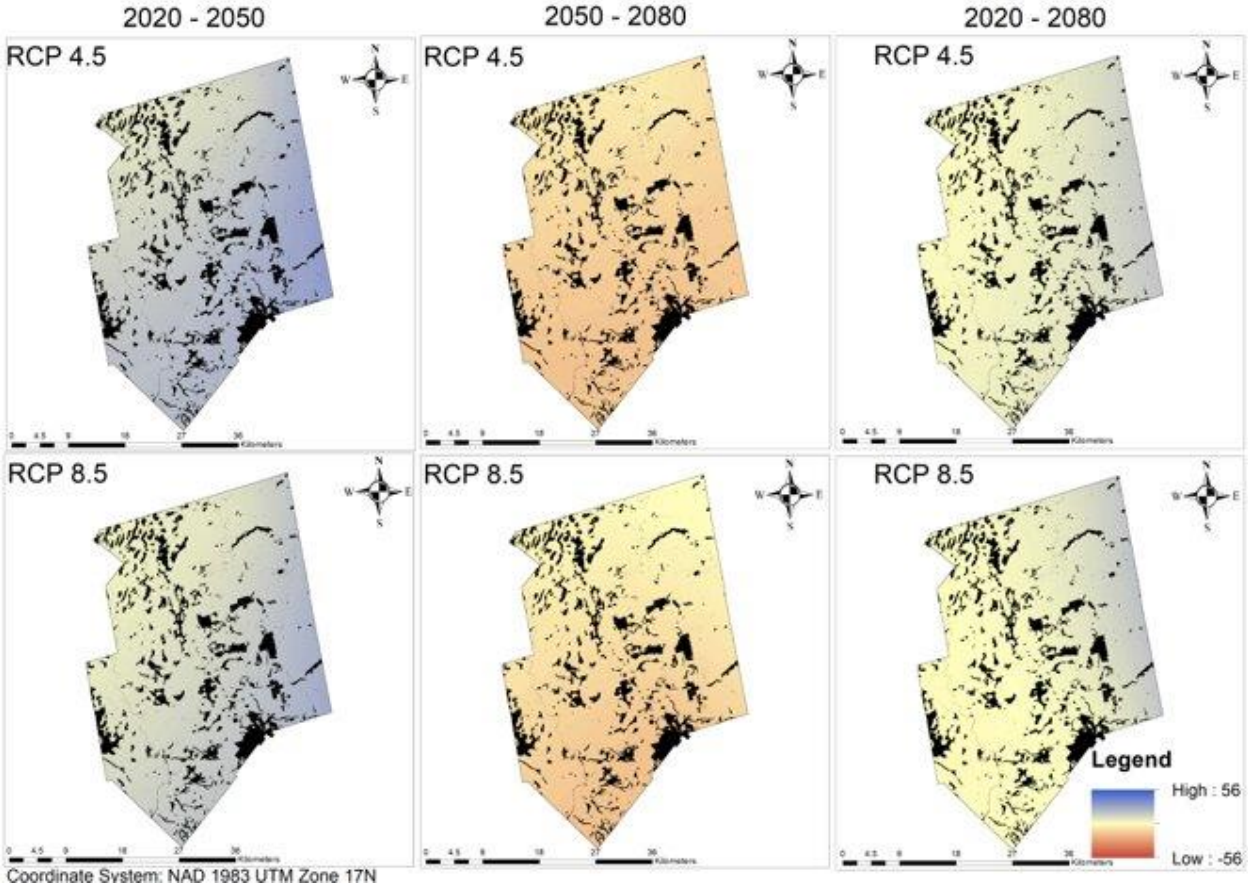


Figure 12: Continuous change detection maps for potato between 2020 – 2050, 2050 – 2080 and 2020 – 2080

Table 12: Mean percent change in suitability for potato production over each time period and scenario

Scenario and Time Period	Mean Change (% Suitability)
RCP 4.5 2020 - 2050	15.71
RCP 4.5 2050 - 2080	-10.44
RCP 4.5 2020 - 2080	5.27
RCP 8.5 2020 - 2050	11.02
RCP 8.5 2050 - 2080	-7.52
RCP 8.5 2020 - 2080	3.50

5. Discussion & Conclusion

5.1 Discussion

Due to the nature of forecasting climate variables, it is difficult to project at the very fine spatial scales needed for this analysis. Forecasted variables used are only estimates and with this can cause accuracy issues when looking at each scenario and year separately. Therefore, looking at overall trends of the analyses is more helpful for the purpose of this study.
Overall, our results seem to match research about effects of climate change on temperate climate agriculture. Looking at change detection by each crop from 2020 – 2080; maize will have the highest positive change due to average temperatures and total precipitation becoming closer to optimal levels, potatoes end with little change even though temperatures are becoming less suitable due to increased precipitation, while soybean sees a positive change on the Eastern side of Dufferin however may not have the same effect on the Western part of the county.

One interesting part of each analysis is that they all have a similar trend of areas that become more suitable over time. With all 3 crops having lower suitability in the Southeastern corner of the county currently, however by 2080 all 3 crops have their highest suitability scores in this area. We cannot determine the exact reason for this, but it seems that future climate could favour this area for crop growth and should be studied before development if possible.

5.2 Strengths & Limitations

Agriculture and food security are expected to become increasingly important in the future. There are many factors and variables that can affect suitability of land to grow certain crops, but existing literature, data availability, and time constraints limited factors we could use in the analysis. Despite literature outlining their importance in crop growth, we could not include soil pH or depth in our analysis due to limited data availability. Including pH may have altered our results because of the way that the expected increase in temperature and humidity could decrease soil pH over time ("Acidification," n.d.). Due to ongoing and incomplete soil data in Ontario, as well as to avoid inconsistencies from changes in data collection instruments and techniques between survey dates, we opted to use data from the first survey. Unfortunately, this means that our soil data may be outdated or inaccurate, and some of the suitability issues we saw may have been resolved since the initial survey.

Although we understand that much of the type and quantity of crops that farmers grow relies on economics, we decided not to include future market price as a variable in our analysis. We believe that our research is more useful as a tool to help guide farmers' decisions on what, where, and how to plant certain crops in Dufferin County without dictating absolutes.

An important factor to consider in any MCE analysis is the inherent bias present from researchers assigning factor weights and relative importance to different variables. To minimize bias, we thoroughly researched our variables and their agricultural impacts. Furthermore, we consulted a representative from the Municipality of Dufferin in order to make the most informed judgements of our factor weights.

5.3 Recommendations & Future Research

Based on our results, we would like to make general recommendations regarding future management of agricultural lands in Dufferin County, as well as suggest related topics that would benefit from further research. Although average temperature is expected to increase, approaching more suitable values for certain crops' growth, it is unclear how many days within a growing season are above or below threshold values. Too many days outside of the suitable range (especially in a row) could lead to entire fields of crops failing, so quantifying these days is of increasing importance. Evaporation is also likely to increase due to increasing temperatures. Combined with potentially more intense but infrequent precipitation events, excess drying of soils and resultant decrease in soil permeability could be a problem. If irrigation becomes necessary, increased evaporation could create a mineral crust on agricultural fields, also negatively impacting soil permeability. Research on the likelihood on these issues occurring in the changing climate must be looked into.

We would like to reiterate the importance of soil conservation practices, especially in a changing climate that could lead to increased topsoil erosion through new precipitation and wind patterns. There are areas of land on the Greenbelt in Dufferin County that are currently unsuitable for agriculture due to topsoil erosion (Figure 13). If soils continue to degrade, then more suitable future climates become irrelevant. Quantifying potential topsoil losses, future research may include more specific analysis of future precipitation patterns, including average and anomaly IDF curves (Intensity, Duration, Frequency), as well as future precipitation patterns. Water runoff management practices may also need revision in the coming years.

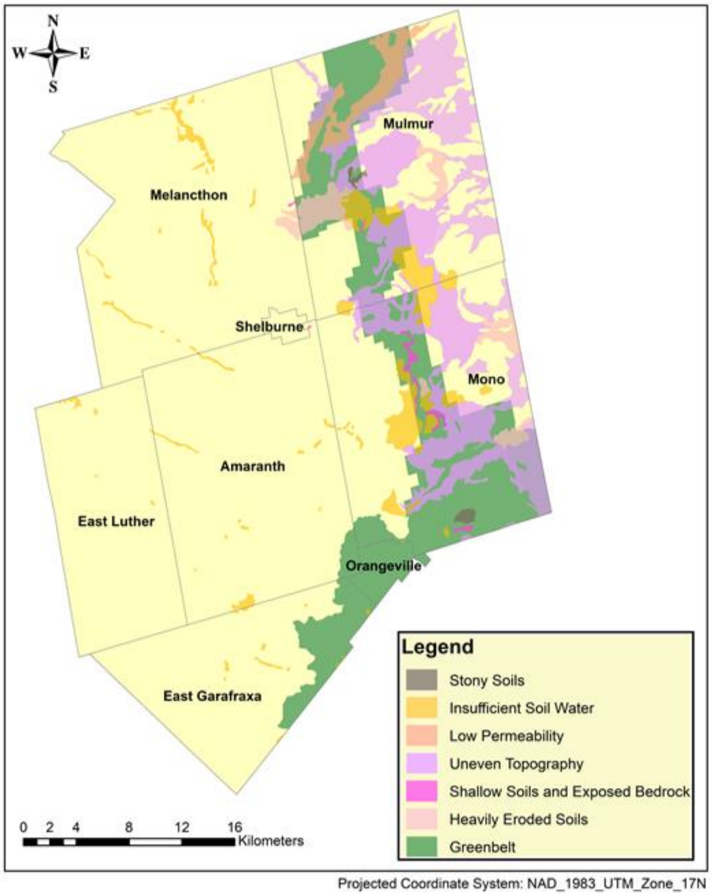


Figure 13: Parcels of land in Dufferin County designated under Soil Capability Classes 6 and 7, where it is deemed unfeasible to improve soil conditions for agriculture

The same climate variables analyzed in our study that may increase crop suitability could also increase habitat suitability for various pest species. Therefore, we recommend research aimed at determining future pest suitability, as well as likelihood, frequency, and/or severity of future pest outbreaks. Following this, research on the effects of potential increases in pesticide use on Dufferin County's water quality may be necessary.

Lastly, our research focused on crops currently being grown in Dufferin County. It is possible that the most well-suited crops in the future are completely different from those we analyzed. Further research on how different crops and GMO crops may increase yields under future climate scenarios could also be beneficial.

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7. Appendix

7.1 Appendix A: Data Information

Table 13: Data used and sources for the project

Data	Data Source	Date of Last Data Modification	Scale
Ontario Hydro Network (OHN) Waterbody.shp	Ontario Ministry of Natural Resources and Forestry - Provincial Mapping Unit	2018-07-12	1:10000
Ontario Road Network: Road Net Element.shp	Ontario Ministry of Natural Resources and Forestry - Provincial Mapping Unit	2019-09-27	Provincial
Built-Up Area.shp	Ontario Ministry of Natural Resources and Forestry	2019-09-04	Provincial
Greenbelt Outer Boundary.shp	Ontario Ministry of Municipal Affairs and Housing	2017-05-18	Provincial
PDEM.tif	Ontario Ministry of Natural Resources and Forestry - Provincial Mapping Unit	2018-10-15	30 m resolution
Soil Survey Complex.shp	Ontario Ministry of Agriculture, Food and Rural Affairs	2019-11-06	Provincial
Historical Temperature and Precipitation	Climate Canada, 2020	2020-12-10	N/A
Projected Temperature and Precipitation	Climate Change Canada, 2020	2020-12-10	N/A
Dufferin County.shp	Ontario Ministry of Municipal Affairs and Housing	2019-12-31	Provincial

Data Sources

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Provincial digital elevation model - Ontario Data Catalogue. (2018). Retrieved February 10, 2021, from https://data.ontario.ca/dataset/provincial-digital-elevation-model

Table 14: Proximity and coordinates of weather stations used for climate point data

Station Name	Proximity to Centre of Dufferin (km)	Latitude (N)	Longitude (W)	Elevation (m)
Ruskview	17.98	44°14	80°08	472
Orangeville Moe	20.09	43°55	80°05	412
Proton Station	27.00	44°10	80°31	480
Alliston Station	27.46	44°09	79°52	221
Albion Field Centre	34.53	43°55	79°50	282
Egbert Care	37.49	44°14	79°47	252
Fergus Shand Dam	39.66	43°44	80°19	418
Cookstown	42.83	44°12	79°41	244
Essa Ont Hydro	42.97	44°21	79°49	216
Bradford Muck Research	48.31	44°02	79°36	221
Durham	50.47	44°11	80°49	384

Table 15: Pairwise comparison of each criterion

Criteria	**Mean Monthly Temperature**	**Mean Monthly Precipitation**	**Slope**	**Soil Texture**	**Soil Drainage**	**Sum**
Mean Monthly Temperature	1	3	0.1429	0.3333	0.3333	4.8095
Total Precipitation	0.3333	1	0.1429	0.3333	0.3333	2.1428
Slope	7	7	1	5	5	25
Soil Texture	3	3	0.2	1	1	8.2
Soil Drainage	3	3	0.2	1	1	8.2

Table 16: Individual weights for each criterion

Criteria	**Mean Monthly Temperature**	**Mean Monthly Precipitation**	**Slope**	**Soil Texture**	**Soil Drainage**	**Total Weights**
Mean Monthly Temperature	0.2079	0.1556	0.28	0.3659	0.3659	0.275
Total Precipitation	0.6238	0.4667	0.28	0.3659	0.3659	0.4204
Slope	0.0297	0.0667	0.04	0.0244	0.0244	0.037
Soil Texture	0.0693	0.1555	0.2	0.122	0.122	0.1337
Soil Drainage	0.0693	0.1555	0.2	0.122	0.122	0.1337
Sum	1	1	1	1	1	1

7.2 Appendix B: Flowcharts

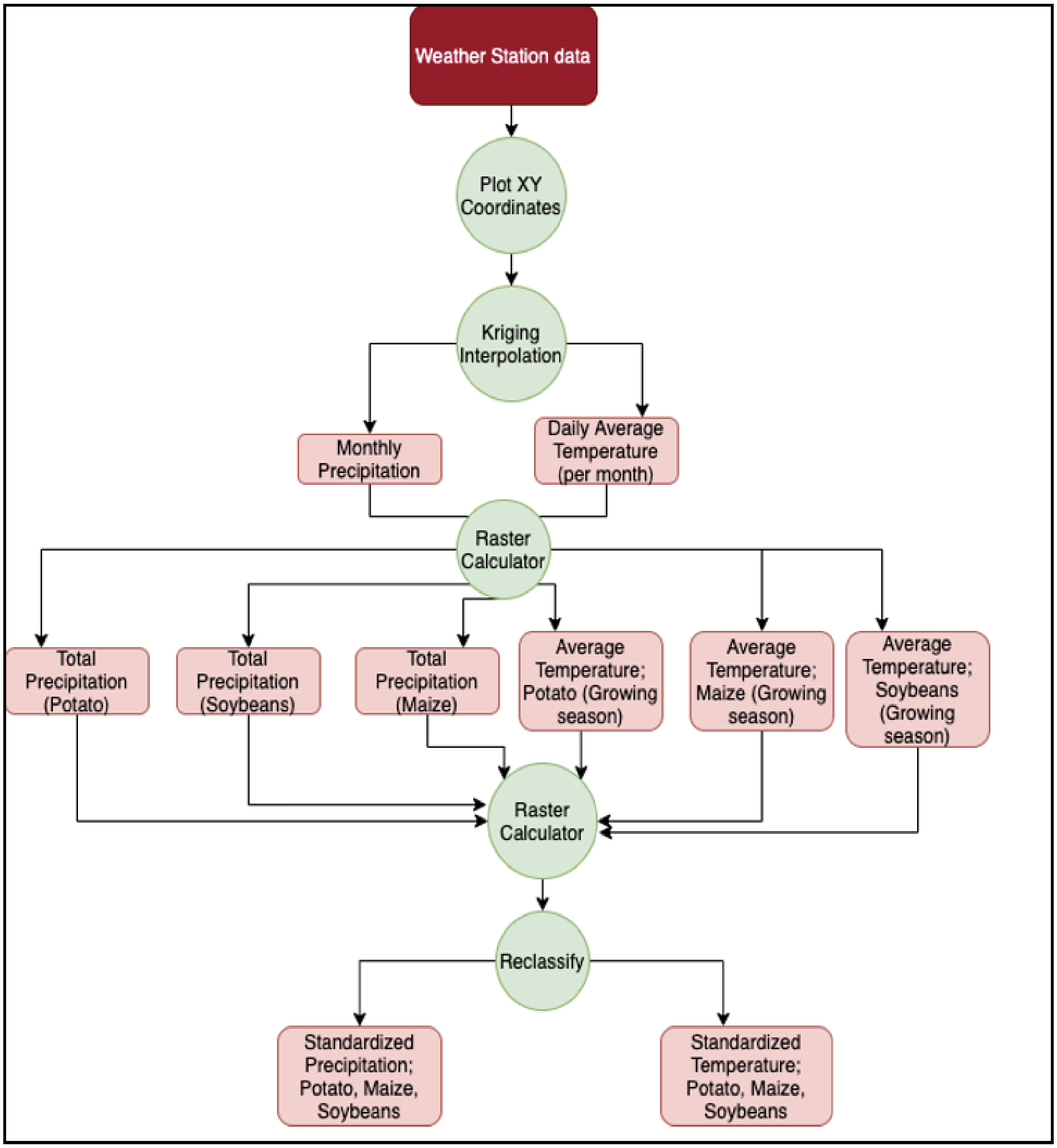


Figure 14: Flowchart for weather station data

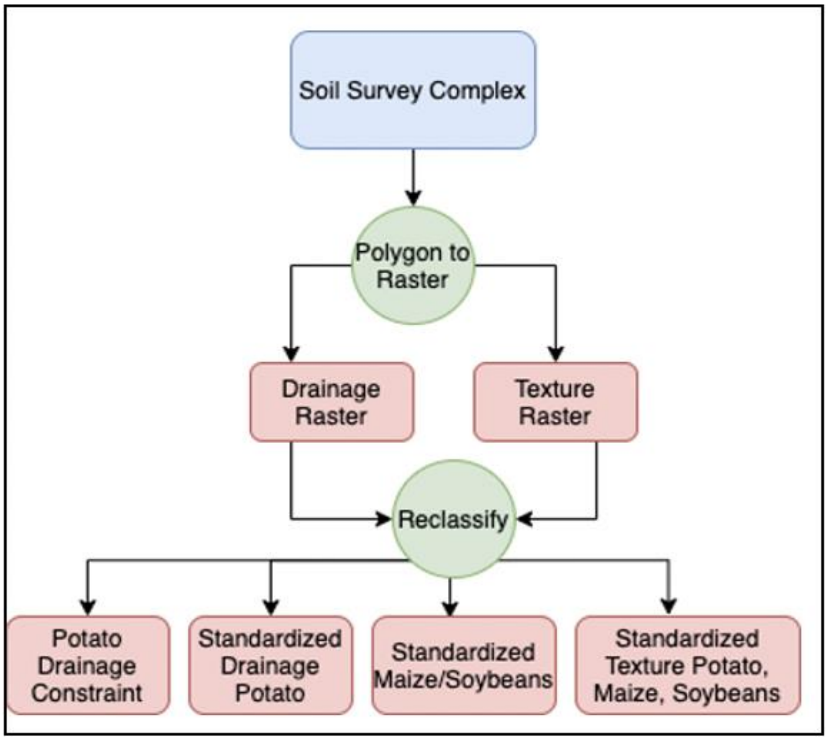


Figure 15: Flowchart for processing Soil Survey Complex data

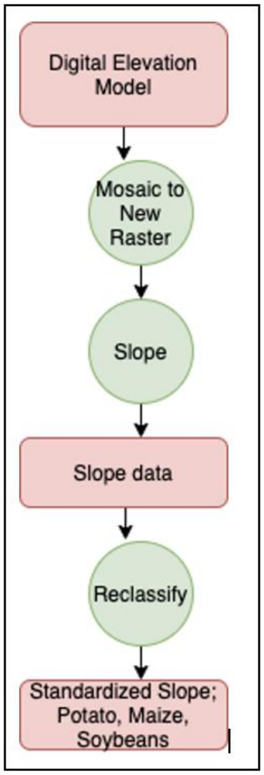


Figure 16: Flowchart for processing Slope data

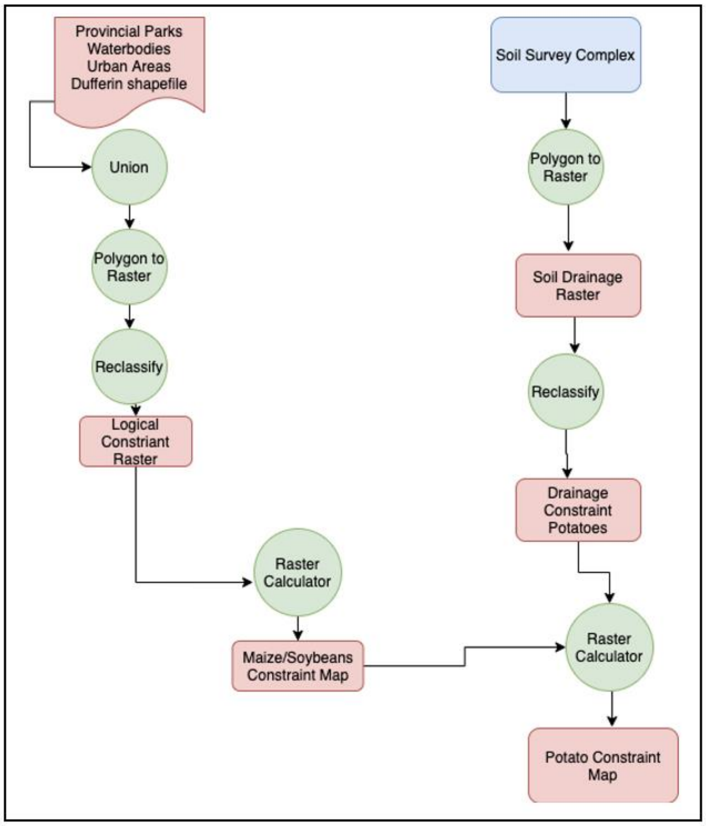


Figure 17: Flowchart for processing Crop Constraints

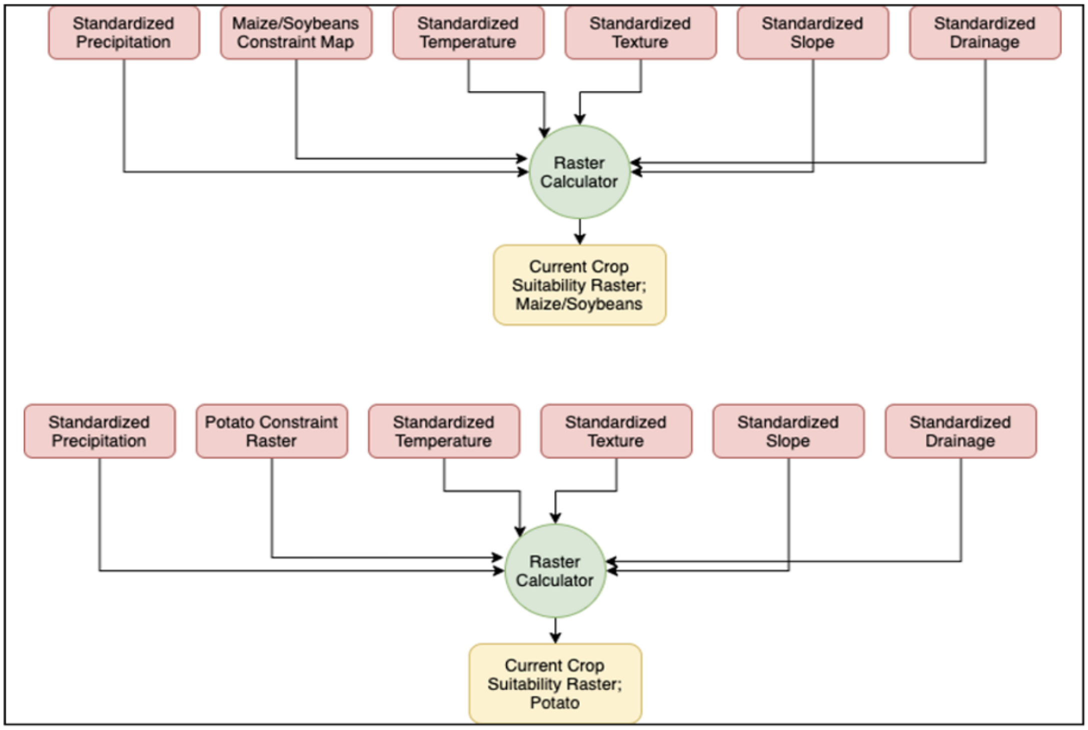
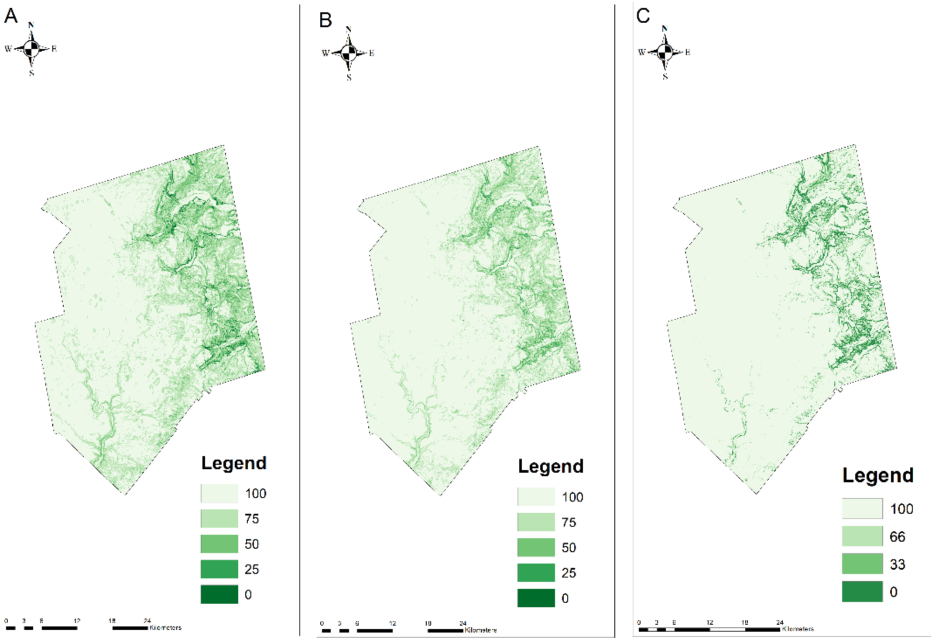


Figure 18: Flowchart for creating Current Crop Suitability Raster

7.3 Appendix C: Standardized Variable Maps

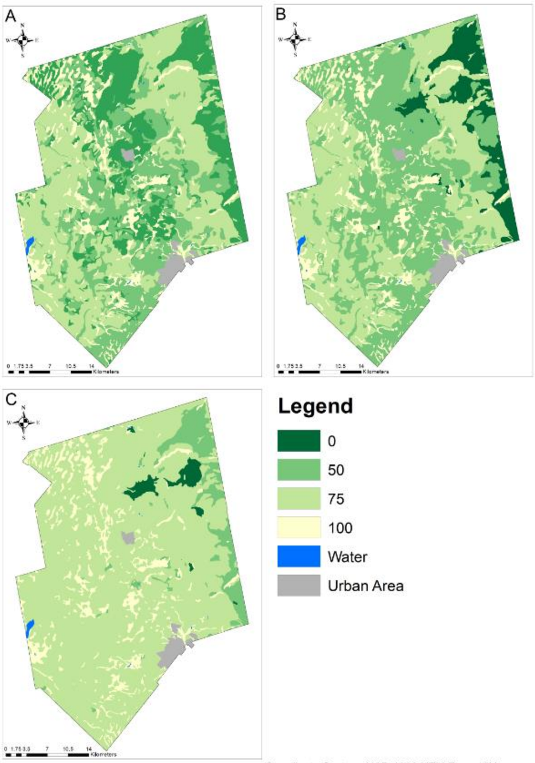
Slope



Coordinate System: NAD 1983 UTM Zone 17N

Figure 19: Slope Standardized for (A) maize, (B) soybean, and (C) potato

Texture



Coordinate System: NAD 1983 UTM Zone 17N

Figure 20: Standardized soil texture rasters for (A) maize, (B) soybean and (C) potato

Drainage

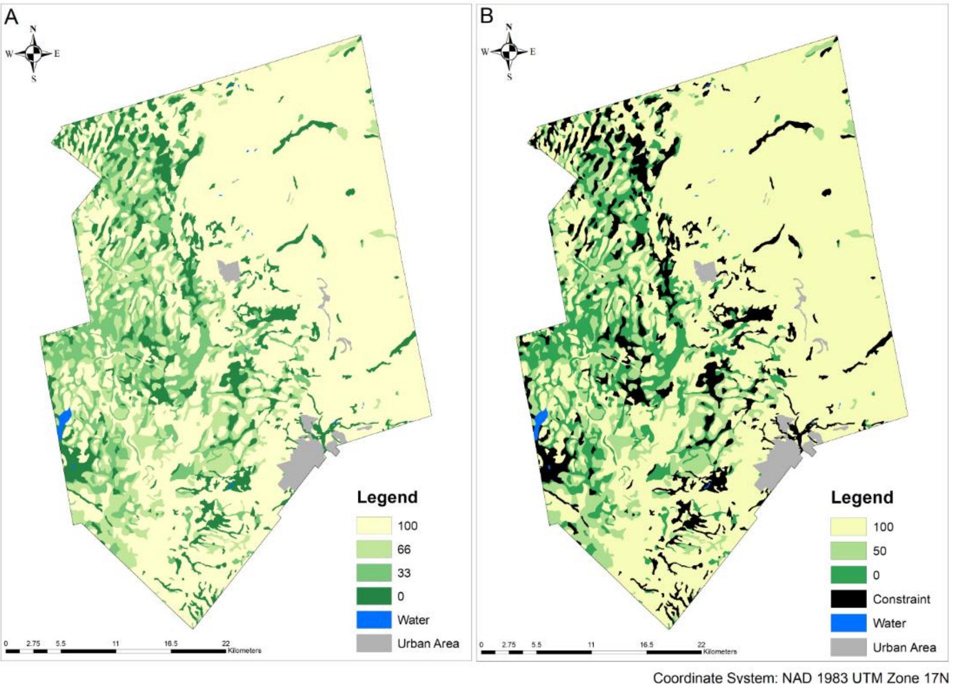


Figure 21: Standardized soil drainage rasters for (A) maize and soybean & (B) potato

Climate Variables

Table 17: Maximum and minimum values used to standardize climate variables of each crop across current and projected scenarios

Crop Type	Maximum Temperature (°C)	Minimum Temperature (°C)	Maximum Precipitation (mm)	Minimum Precipitation (mm)
Maize	22.605	15.386	460.736	403.821
Potato	19.3001	12.627	410.801	308.575
Soybean	24.038	16.390	365.588	318.987

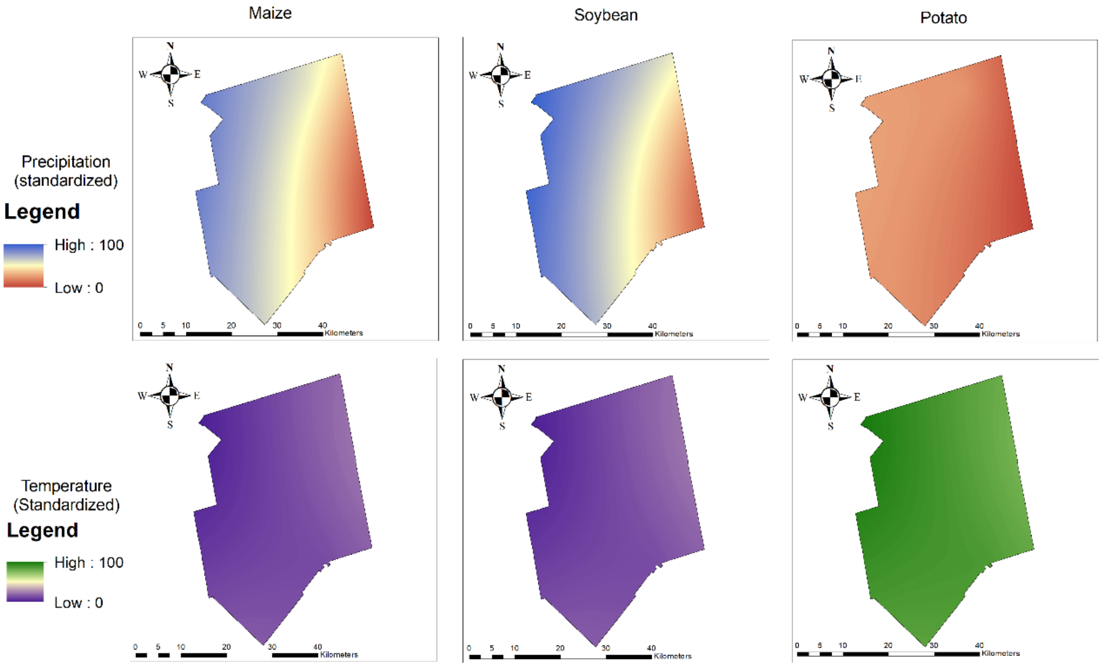


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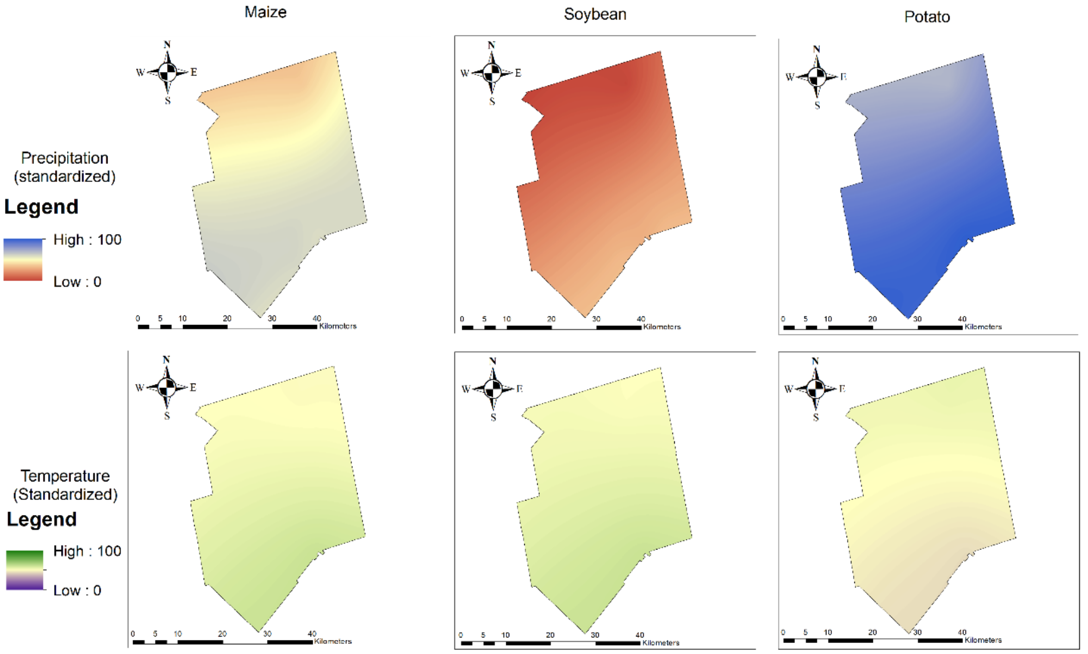
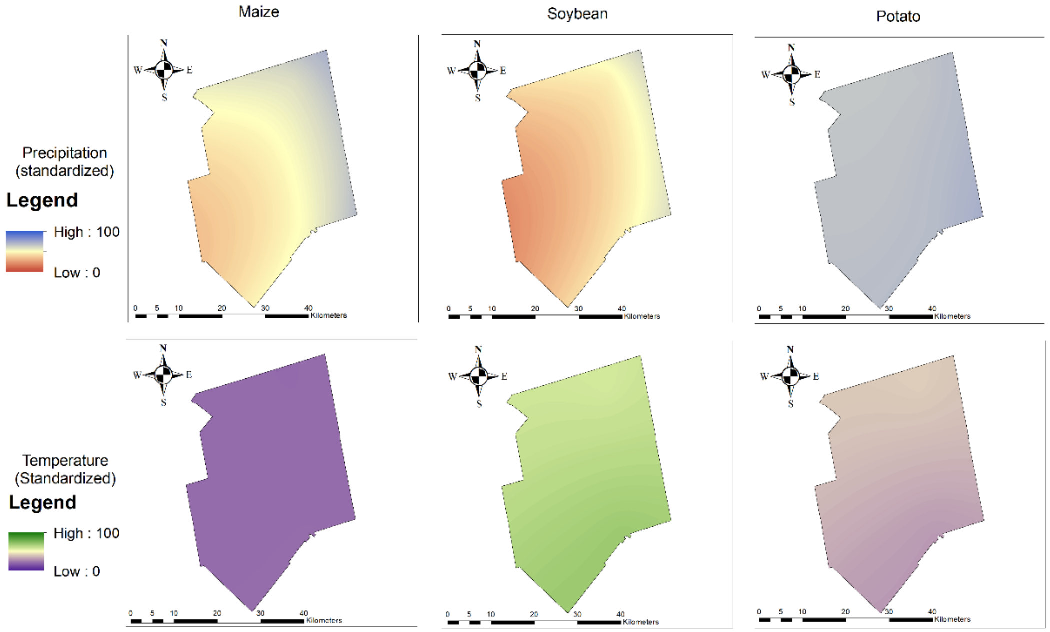
Figure 22: Current temperature and precipitation rasters standardized by crop



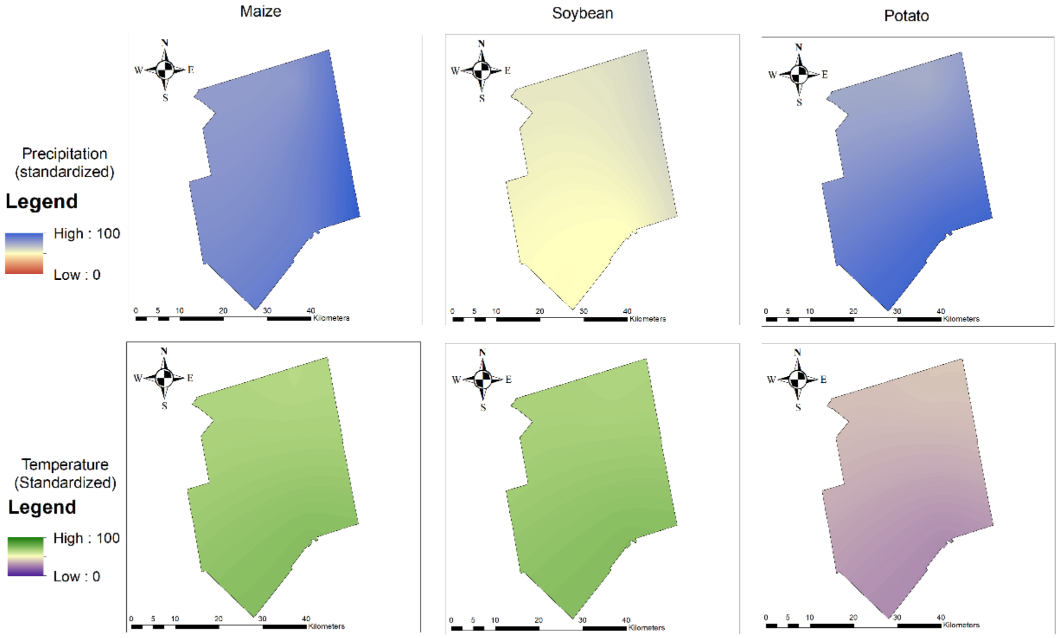
Coordinate System: NAD 1983 UTM Zone 17N

Figure 23: RCP 4.5, year 2050 temperature and precipitation rasters standardized by crop



Coordinate System: NAD 1983 UTM Zone 17N

Figure 24: RCP 4.5, year 2080 temperature and precipitation rasters standardized by crop



Coordinate System: NAD 1983 UTM Zone 17N

Figure 25: RCP 8.5, year 2050 temperature and precipitation rasters standardized by crop

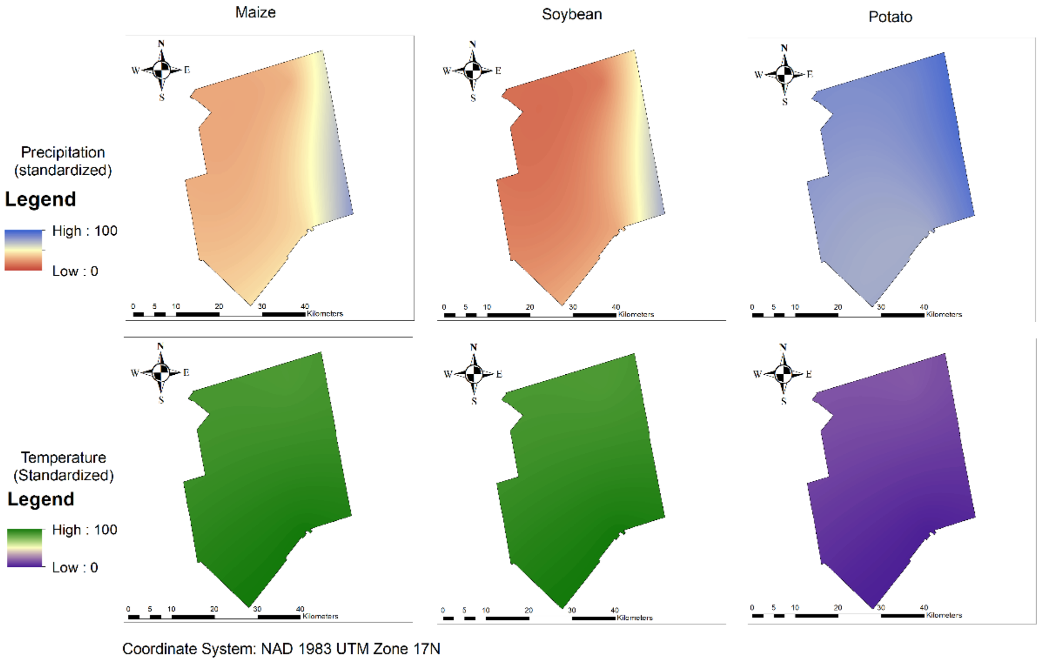


Figure 26: RCP 8.5, year 2080 temperature and precipitation rasters standardized by crop