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MODELLED CLIMATE CHANGE IMPACTS ON SPRING CANOLA PRODUCTION ACROSS BRITISH COLUMBIA, CANADA

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Abstract

This paper investigates the impact of projected near future climate trends on the production of spring planted canola (*Brassica napus*, *Brassica rapa*, and *Brassica juncea* of canola classification) across British Columbia, Canada. Analysis of historic climate trends from 2001-2020, informed by the Global Historical Climatology Network daily (GHCNd) database, establishes patterns of warming temperatures and increasing precipitation values across the province over the early 21st century. Near future climate trends were modelled using CMIP6 climate models, from 2021-2040 under SSP1-2.6, SSP2-4.5 and SSP5-8.5, with the projections downscaled using ClimateBC. The projected trends mirrored those of the observed historic record, while an observable relationship between rising levels of climate change and increasing projected annual precipitation and temperature is recorded. The subsequent crop modelling using the CSM-CROPGRO-Canola and DNDC models, fed with the modelled climate trends, highlighted the expectation for near future climate change to cause significant decreases in spring canola production across British Columbia.

Keywords**:** British Columbia, canola, climate change.

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1. Introduction

Climatic factors are a key determiner on crop growth, with anthropogenic climate change representing major challenges for agricultural management across the world (Aggarwal et al., 2019). The sensitivity of crops to both temperature and precipitation change, primarily serve as major factors in determining the level of threat that climate change poses and as such, the viability of given production patterns in the future (Gornall et al., 2010).

Canola (*Brassica napus*, *Brassica rapa*, and *Brassica juncea* of canola classification) (Wanasundara et al., 2017) is specifically sensitive to climatic changes. This is due to canola being an annual crop with a short growth cycle, alongside it being planted in both spring months and winter months (referred to as spring and winter canola respectively) and thus, being grown across the entire calendar year (Daun, 2011). Within Canada specifically however, spring planted canola dominates production – due to the extremely harsh conditions of Canadian winters threatening the growth of a mild-condition crop such as canola (Page et al., 2021).

Canada is especially threatened by climate change, being reported to be experiencing warming at a rate double to that of the rest of the world on average (Wang et al., 2022) - attributable to its unique geographical setting (Ball, 2022). In the short term however, cooler areas of the province are expected to benefit positively from climate change – it has been observed that spring canola production across the last century has increased markedly nationwide, specifically correlating with increases to both temperature and precipitation due to climate change (Jannat et al., 2022) (Kutcher et al., 2010). However, these projected localised increases in production are not representative of wider trends, especially across extended time periods – with high temperatures and precipitation values presenting as huge limiting variables on Canadian spring canola yield in the future, as they cross a critical threshold and begin to constrain growth due to associated heat and water stress (Qian et al., 2018).

Presently, there is a research gap surrounding an evaluation of modelled future climate change – using CMIP6 climate models and shared socioeconomic pathways (SSPs) –paired with crop modelling, to assess future canola production across British Columbia. Previous studies have employed CMIP5 climate models and corresponding relative concentration pathways (RCPs) (Qian et al., 2018), but there is currently a lack of more recent, contemporary projections utilizing CMIP6 climate models. The necessity of this renewed investigation arises from the value such updated conclusions hold for canola producers, in directing adaptive measures in relation to the projected impacts of climate change. With this value being further strengthened against the context of trending increases of canola production within British Columbia, with production expected to continue to increase across the future (Barthet, 2016).

1.1 Case Study Locations

Spring canola production across British Columbia is primarily concentrated across the Peace River region, with the area accounting for over 80% of total grain and oilseed crop production in the province (Government of British Columbia, 2021). This is primarily due to the conditions of the area being favourable to early-maturing crops, such as canola, with longer days and extended frost-free periods resulting in increased yields (Peace River Regional District, 2014).

British Columbia informs a large amount of its provincial scale decision making from areas that are under the dedicated Agricultural Land Reserve (ALR) scheme (Perez et al., 2015). Established in 1973 the ALR spans the entire province, mapped in figure 1, and serves to protect roughly 5 million hectares of farmland by incentivising farming in the area and limiting non-agricultural uses (Androkovich et al., 2008).

Resultantly, the ALR serves as a valuable tool in outlining key agricultural areas across the province – from which the three specific case study locations of this study are drawn:

1) **Peace River - Fort St. John**
   Main canola producing region of British Columbia (Peace River Regional District, 2014). Refer to figure 2.
2) **Cariboo - Williams Lake**
   Most expansive agricultural area, based on ALR classifications. Refer to figure 2.
3) **Northern Rockies Regional Municipality - Fort Nelson**
   Northern most agricultural area, based on ALR classifications. Refer to figure 2.

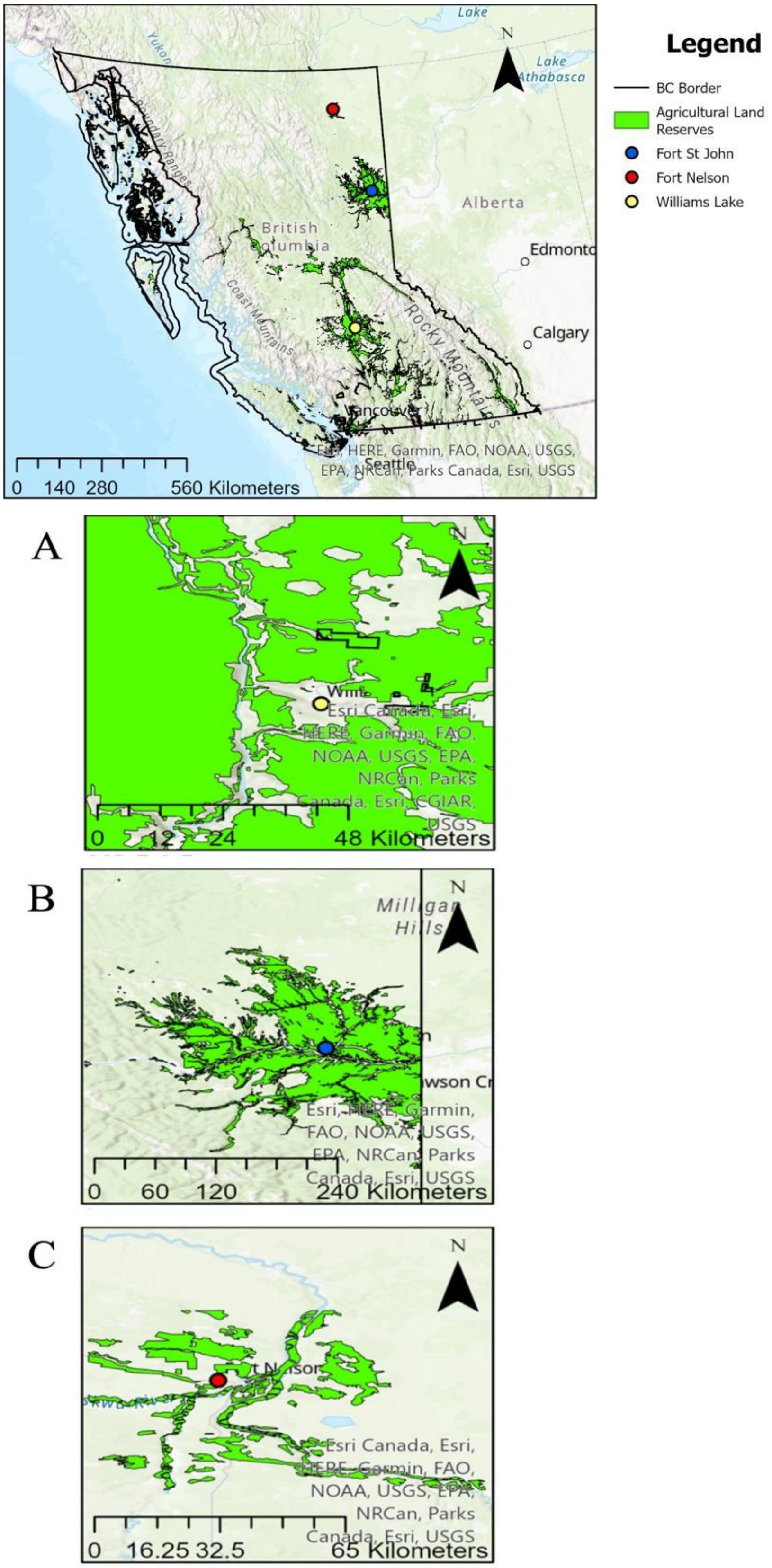


Figure 1 – Province wide overview map, alongside study locations A) Williams Lake (52.128429, -122.130203), B) Fort St. John (56.246464, -120.847633), C) Fort Nelson (58.8035, -122.6912.)

2. Methodology

The methodology workflow is depicted in figure 2.

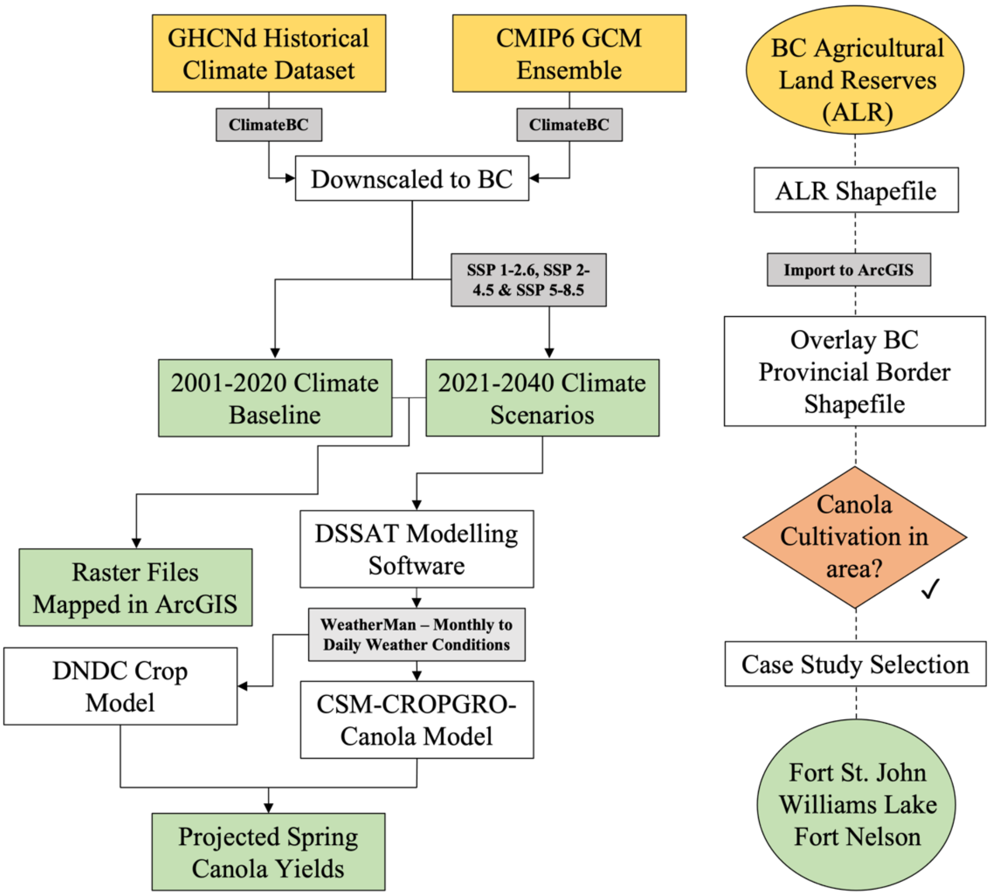


Figure 2 - Methodology Workflow Diagram

2.1 Historic Climate Conditions

As covered in the diagram above, the historical climate data that underpins this study is developed from weather station observations from the Global Historical Climatology Network daily (GHCNd) database. The database includes daily climate variable summaries from land surface stations across the globe (National Centers for Environmental Information, 2021).

The GHCNd daily summaries are then downscaled within the ClimateBC application (version 7.30), to scale-free point locations across the province of British Columbia, with the downscaling achieved through a combination of bilinear interpolation and dynamic local elevation adjustment (Wang et al., 2016).

2.2 Historic Canola Statistics

To allow for comparison between historic levels and patterns of canola production, historical canola statistics for British Columbia are sourced from the Canadian Grain Commission’s annual reports entitled “Quality of Western Canadian Canola [YEAR]” (Canada Grain Commission, 2022). Given the baseline period of 2001-2020, the annual reports across this 20-year period were used.

2.3 Emission Scenarios

A key input to ClimateBC to inform the modelling of near future climate change is the selection of three individual shared socio-economic pathway (SSP) emission scenarios.

Each SSP scenario represents a unique projection for how society and associated development will evolve and be fuelled across the 21st century (van Vuuren et al., 2017).

The SSPs selected include:

1. SSP1-2.6, representative of an immediate switch to "sustainable" development (Meinshausen et al., 2020).
2. SSP2-4.5, a "middle of the road" scenario, where some progress has been made to reduce the overreliance on fossil fuels for development (Meinshausen et al., 2020).
3. SSP5-8.5, development fuelled entirely by fossil-fuels (Meinshausen et al., 2020).

2.4 Future Climate Modelling

The 2021-2040 projected climate scenarios are generated using ClimateBC, through downscaling an ensemble of 13 CMIP6 process-based climate models - with typical resolutions of 250 km in the atmosphere and 100 km in the ocean (Liang-Liang et al., 2021) - to scale-free point locations across British Columbia, with a mean latitudinal resolution of 1.4° (range of 0.7°–2.8°) (Mahony et al., 2022). The downscaling is achieved with the same process of bilinear interpolation and dynamic local elevation adjustment as used for the historical data (Wang et al., 2016).

The climate modelling is run for 2021-2040, for each of the three SSPs (1-2.6, 2-4.5 & 5-8.5), again on both a provincial scale and for the three individual case study locations of Williams Lake, Fort St. John and Fort Nelson. With a 20-year period both matching the length of the observed historic period and allowing sufficient time for the impacts of the varying SSPs to be fully experienced.

2.4.1 Bias Analysis & Model Selection

Before being included in ClimateBC, all of the models included in the CMIP6 ScenarioMIP were assessed against several criteria, prior to bias analysis, to inform the selection of the ensemble (Mahony et al., 2022). This resulted in 19 viable models prior to bias analysis, being limited to 13 models in the final ensemble following the analysis - due to high biases and models sharing components / institutions of origin (refer to figure 3 and table 1).

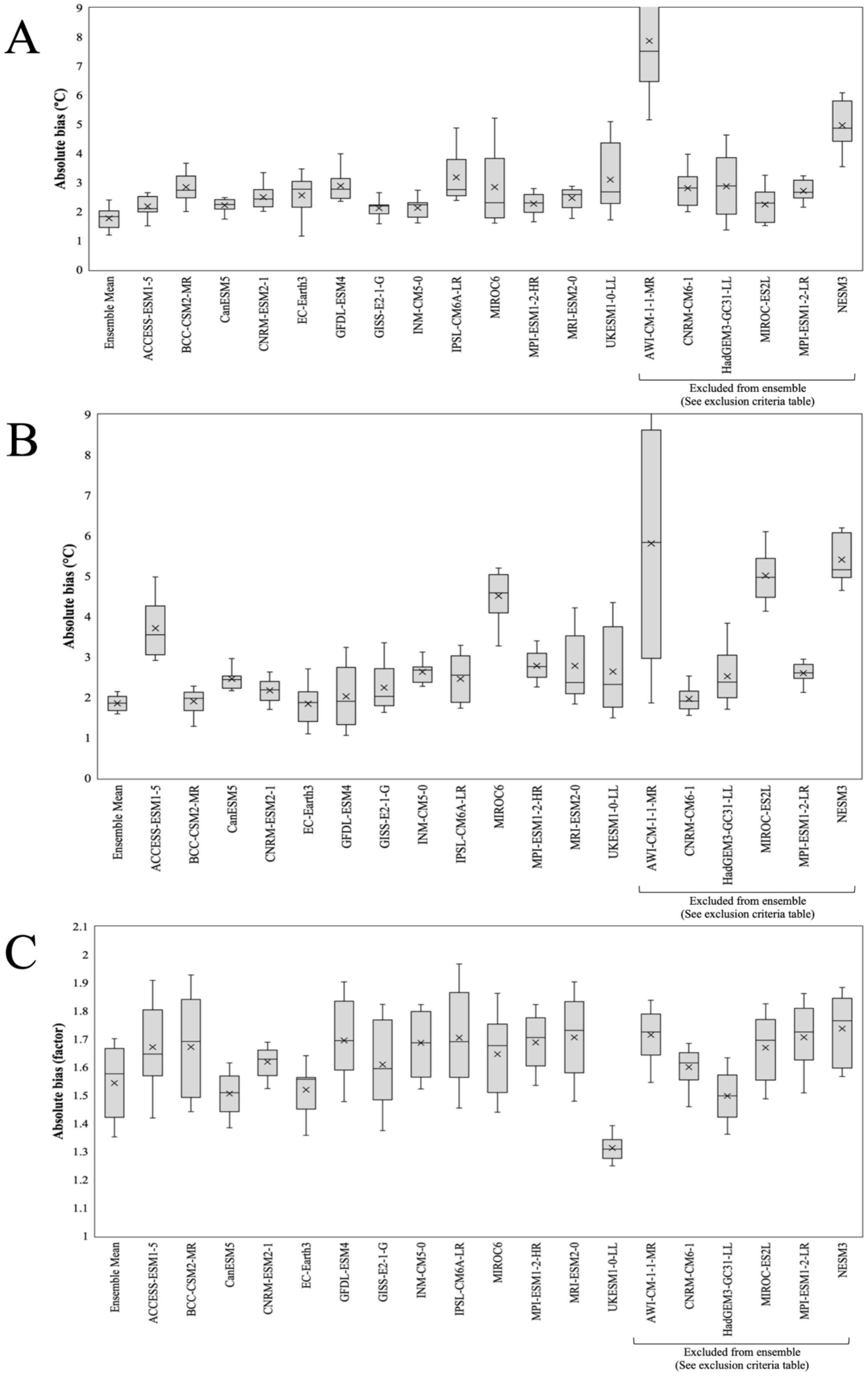


Figure 3 - Model absolute biases of monthly means of A) daily maximum temperature (°C), B) daily minimum temperature (°C), C) precipitation, expressed as a factor of magnitude. Adapted from Mahony et al. (2022)

Table 1 – CMIP6 ScenarioMIP models, alongside reasons for exclusion. Selected models are highlighted in green. Adapted from Mahony et al. (2022)

Model	***Reason for exclusion***
ACCESS-CM2 2	<3 historical runs
ACCESS-ESM1-5	
AWI-CM-1-1-MR	High bias
BCC-CSM2-MR	
CAMS-CSM1-0	No tmax/tmin
CESM2	No tmax/tmin in historical
CESM2-WACCM	No tmax/tmin in historical
CIESM	Incomplete SSP scenarios
CMCC-CM2-SR5	No tmax/tmin
CNRM-CM6-1	Same institution
CNRM-CM6-1-HR	<3 historical runs
CNRM-ESM2-1	
CanESM5	
CanESM5-CanOE	Same institution
E3SM-1-1	Incomplete SSP scenarios
EC-Earth3	
EC-Earth3-AerChem	<3 historical runs
EC-Earth3-Veg	Same institution
FGOALS-f3-L	No tmax/tmin
FGOALS-g3	No tmax/tmin
FIO-ESM-2-0	Incomplete SSP scenarios
GFDL-CM4	Incomplete SSP scenarios
GFDL-ESM4	
GISS-E2-1-G	Selected r*ilp3fl variants
HadGEM3-GC31-LL	Shared components (UKESM1)
HadGEM3-GC31-MM	Incomplete SSP scenarios
IITM-ESM	No tmax/tmin
INM-CM4-8	<3 historical runs
INM-CM5-O	
IPSL-CM6A-LR	
KACE-1-0-G	No tmax/tmin
KIOST-ESM	<3 historical runs
MCM-UA-1-0	No tmax/tmin
MIROC-ES2L	Same institution
MIROC6	
MPI-ESM-1-2-HAM	Incomplete SSP scenarios
MPI-ESM1-2-HR	
MPI-ESM1-2-LR	Same institution
MRI-ESM2-0	
NESM3	Shared components (MPI-ESM1)
NorESM2-LM	No tmax/tmin
NorESM2-MM	No tmax/tmin
TaiESM1	No tmax/tmin
UKESM1-0-LL	

2.5 Future Canola Yield Modelling

2.5.1 DSSAT Model

The Decision Support System for Agrotechnology Transfer (DSSAT (version 4.8)) was used, specifically running the process-based CSM-CROPGRO-Canola model to model canola growth under the projected climate conditions. The CSM-CROPGRO-Canola model has been notably calibrated and evaluated with various Canadian cultivars of canola under recent growing conditions (Qian et al., 2019) (Jing et al., 2016).

A key element of the DSSAT software is the WeatherMan programme. WeatherMan –which is short for weather data manager – enables stochastic daily weather generation through the use of climate data inputs and linear interpolation (Pickering et al., 1994). The programme itself includes adapted versions of the weather generators WGEN (Richardson and Wright, 1984) and SIMMETEO (Geng et al., 1988), with the adapted SIMMETEO model employed here specifically, due to its ability to calculate minimum and maximum temperature, alongside precipitation, using monthly climate inputs (Pickering et al., 1994).

Once the daily weather parameters for the near future period have been calculated, for each case study location and all SSPs of interest, using the WeatherMan programme, they can be input into the CSM-CROPGRO-Canola model. This is alongside other key parameters related to canola growth, which include:

- Longitude and Latitude (of the respective case study site).
- May 10th was selected as the seeding date, aligning with trends in 2021 (refer to figure 6).
- Invigor5440 canola variety selected – due to its historic dominance (planted on 22
- million acres in Canada between 2008-2017 (RealAgriculture, 2017).
- Sandy loam set for soil type and texture (as the closest match to the Gray Luvisol
- that dominates British Columbia (Canadian Society of Soil Science, 2020).
- Planted in rows as dry seed, at 1 inch depth, with 40 plants per square metre with a
- 25 cm row spacing (all recognised optimum standards) (Bayer Crop Science, 2021)
- (Angadi et al., 2003) (Canola Digest, 2017).

Several outputs are produced from the model runs, with the primary dataset of interest for this study being the PlantGro overview file, which includes statistics of VWAD. VWAD is the amount of modelled newly mature – ready to harvest – canola in weight (stems and leaves in kg/ha) that has been produced on each day following planting. The cumulative totals of annual canola for the near future period, at a given case study site, serves as a representation of how canola production will perform across this location under the degree of climate change represented by the specific SSP modelled.

2.5.2 DNDC Model

The DeNitrification-DeComposition model (DNDC) (version 9.5) was also used to model canola production across the differing SSPs and case study locations. DNDC is a process-based model, which simulates biochemistry under differing soil, climate and agricultural management conditions (Qian et al., 2019). The model has been evaluated for simulating crop yield across Canada, under both present and changing climates alike (He et al., 2018).

Weather inputs for the DNDC model came from the WeatherMan tool included in DSSAT with each set of weather data being exported from the software and then modified to fit the DNDC input format.

They were uploaded as .csv files for each of the modelled years, for each combination of case study location and SSP respectively. This was combined with further inputs including:

- May 10th set as the seeding time, and September 8th as the harvesting date (both
- aligning with 2021 trends).
- No forms of management (e.g., fertiliser application) were selected, following the
- inputs in DSSAT reflecting this.
- Crop conditions were set to be as close to the Invigor5440 cultivar selected in
- DSSAT.
- Soil texture was classified as silty loam, reflecting the choice in DSSAT.

From the model runs, the full breakdown of crop growth for each year was exported. The key variable of interest was annual canola biomass production, in kg C/ha, for each combination of case study location and SSP. The biomass values - mirroring the outputs of VWAD from DSSAT - again serve to illustrate how canola production will be impacted by climate change across the case study locations and SSPs.

2.6 Statistical analysis

2.6.1 Z-score Calculation for Outlier Identification

Z-score calculation is used to identify outliers, so that the assumptions of later statistical tests are met. Z-scores are calculated through the following formula:

$$Z = (X - \mu)/\sigma$$

Where x is the observed value, μ is the distribution mean, and σ is the standard deviation of the distribution (Allen, 2017).

The critical value for z-scores at a 0.05 confidence level is 1.96 (Greenland et al., 2016), therefore any calculated Z-scores either lower than -1.96 or greater than +1.96 can be considered outliers.

2.6.2 Kolmogorov-Smirnov Test

A Kolmogrov-Smirnov test tests for normal distribution, by testing the maximum absolute difference - between the actual values of a sample and the expected values from a normal distribution - against a Kolmogrov-Smirnov Table of critical values (Massey, 1951).

2.6.3 Pearson Correlation Coefficient

Finally, linear correlation is a statistical relationship detailing how related any two variables are, which can be tested for through the calculation of Pearson correlation coefficient (Williams et al., 2020). The test holds two key assumptions – that the data is normally distributed, and that all outliers have been removed – hence the necessity of the Kolmogrov-Smirnov test and Z score calculation that preceded it (Schober et al., 2018).

Pearson correlation coefficient can be calculated using the following formula:

$$\rho = \frac{cov(X, Y)}{\sigma(X) \cdot \sigma(Y)}$$

Where cov is the covariance*,* σ*(X)* is the standard deviation of *X* and σ*(Y)* is the standard deviation of *Y* (Liu et al., 2022).

Pearson correlation coefficients of +1 indicate a perfect positive correlation whereas 0 indicates no correlation, and -1 indicates a perfect negative correlation (Williams et al., 2020).

3. Results

3.1 Historic Climate Results

From the recorded historic climate data for British Columbia, the climate conditions vary significantly between each case study site. A general trend of broad increases in both temperature and precipitation, at each of the case study locations, across the 20-year period is identifiable. However, the degree of such increases differs at each case study location, in addition to the sites' unique inter-annual variability.

Figure 4 notably shows the greatest degree of change in precipitation at Williams Lake, with a range of 256 mm between the start and end of the period. Williams Lake also features a distinctly warmer initial climate – recorded as 6.2°C – however, the site features little change in temperature across the period, with Fort Nelson hosting the greatest change – between 1991 and 2020 values – of 1°C.

Figure 5 provides a valuable visual representation of the trends. There is observably little similarity between the sites in relation to specific inter-annual changes, yet there remains a strong agreement across the case study sites in the wider climate trends on the 20-year scale (1991-2020).

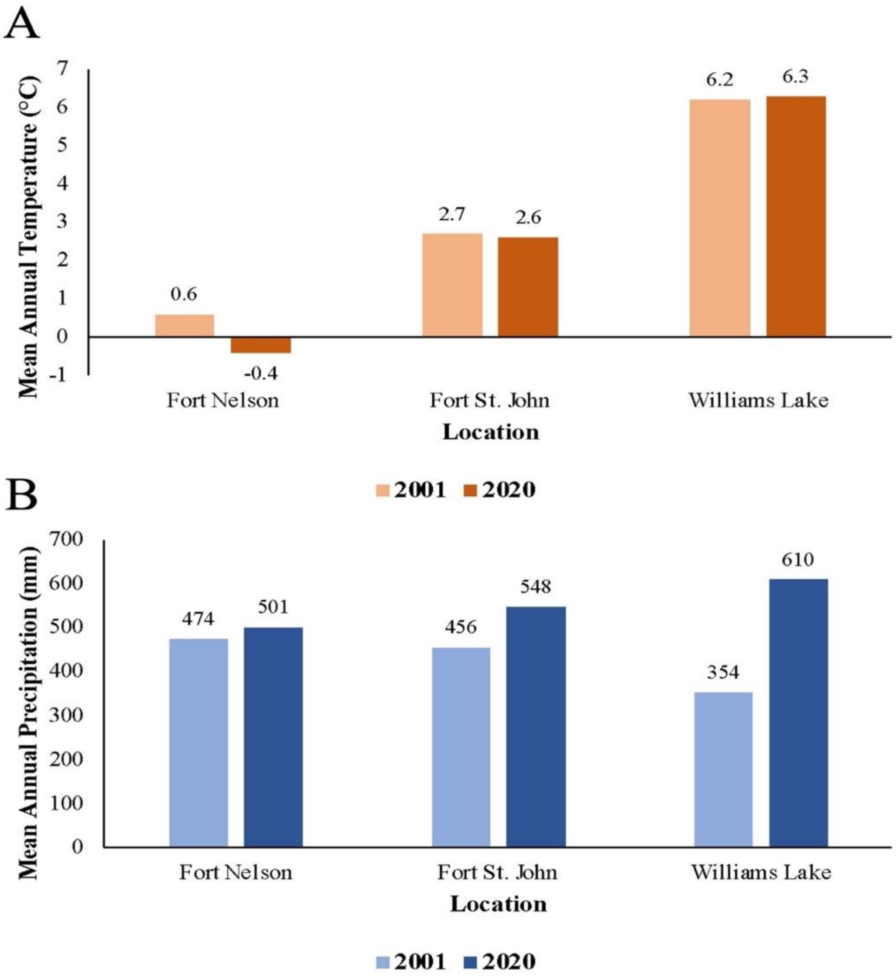


Figure 4 - A comparison of the projected 2001 and 2020 values of A) mean annual temperature and B) mean annual precipitation, for each of the case study locations

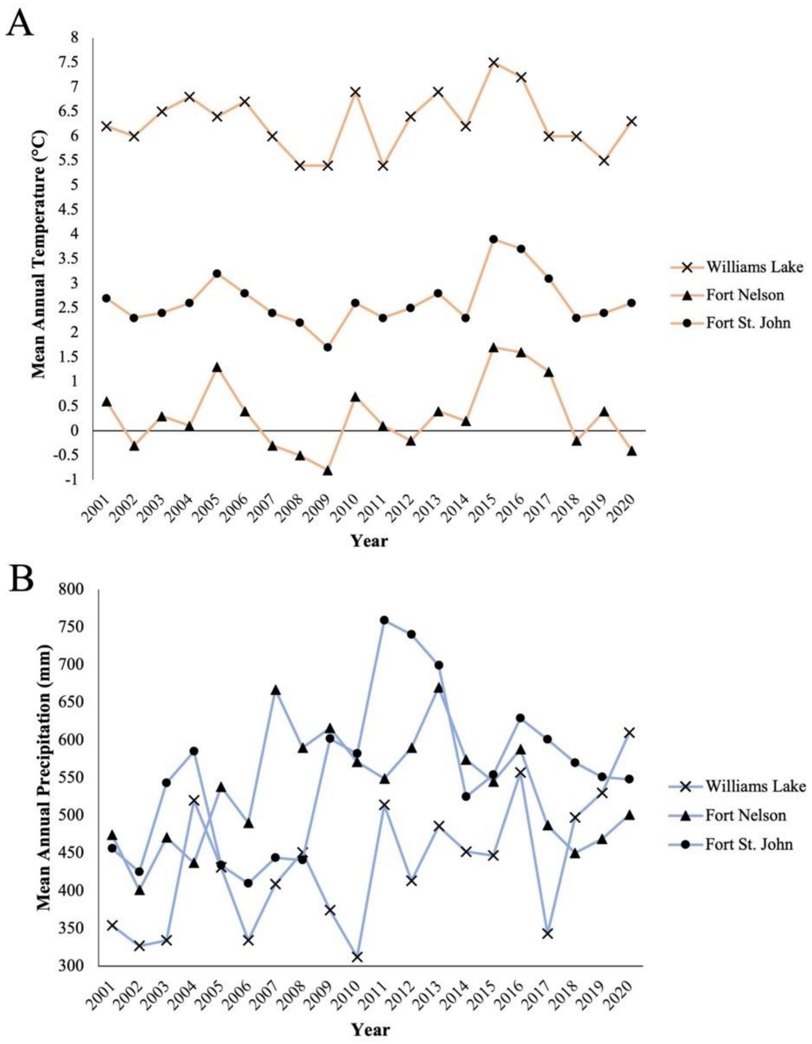


Figure 5 - The progression of A) mean annual temperature, B) mean annual precipitation, from 2001 – 2020 across the case study sites

3.2 Historic Canola Data

Three key statistics were taken from the Canadian Grain Commission's annual reports on the quality of western Canadian canola (Canada Grain Commission, 2022). These included the historic mean canola seeding dates, historic mean harvesting dates and historic annual canola yield, all for the 2001-2020 baseline period. These are each illustrated in figures 6, 7 and 8 respectively - where Julian Day refers to the numerical day of the year, ranging from 1 representing January 1st to 365 (366 if a leap year) representing December 31st.

From 2001 to 2012, there's substantial fluctuation in both seeding and harvesting dates, spanning 85 and 75 days, respectively. This is followed by a stable period starting in 2013, with reduced ranges of 12 and 25 days for seeding and harvesting. The initial variability is reflected, to a lesser extent, in annual yield data, particularly in reduced canola outputs in 2002 and 2009—decreasing by 54% (956 thousand tonnes) and 26% (1149 thousand tonnes), respectively, compared to 2001 and 2008.

Beyond the initial variability, seeding and harvesting dates remain within a two-month window, indicating a consistent trend towards earlier spring canola planting and harvesting. Annual yield figures show a notable upward trend, exemplified by 2017's yield exceeding 2001 by 5135 thousand tonnes (a 290.77% increase). However, between 2017 and 2020, there's a consecutive annual decline, resulting in a cumulative decrease of 1651 thousand tonnes (a 23.92% reduction).

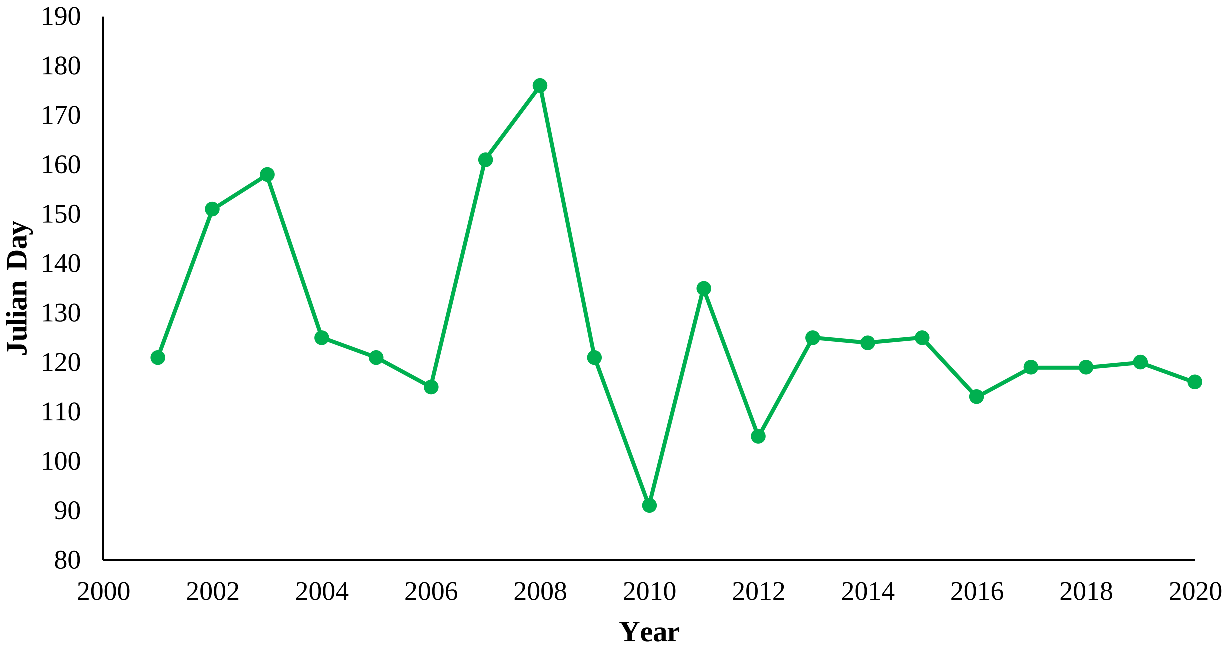


Figure 6 - Historic mean canola seeding dates (2001-2020) for Alberta & the Peace River Region of British Columbia. Data from the Canadian Grain Commission (2022)

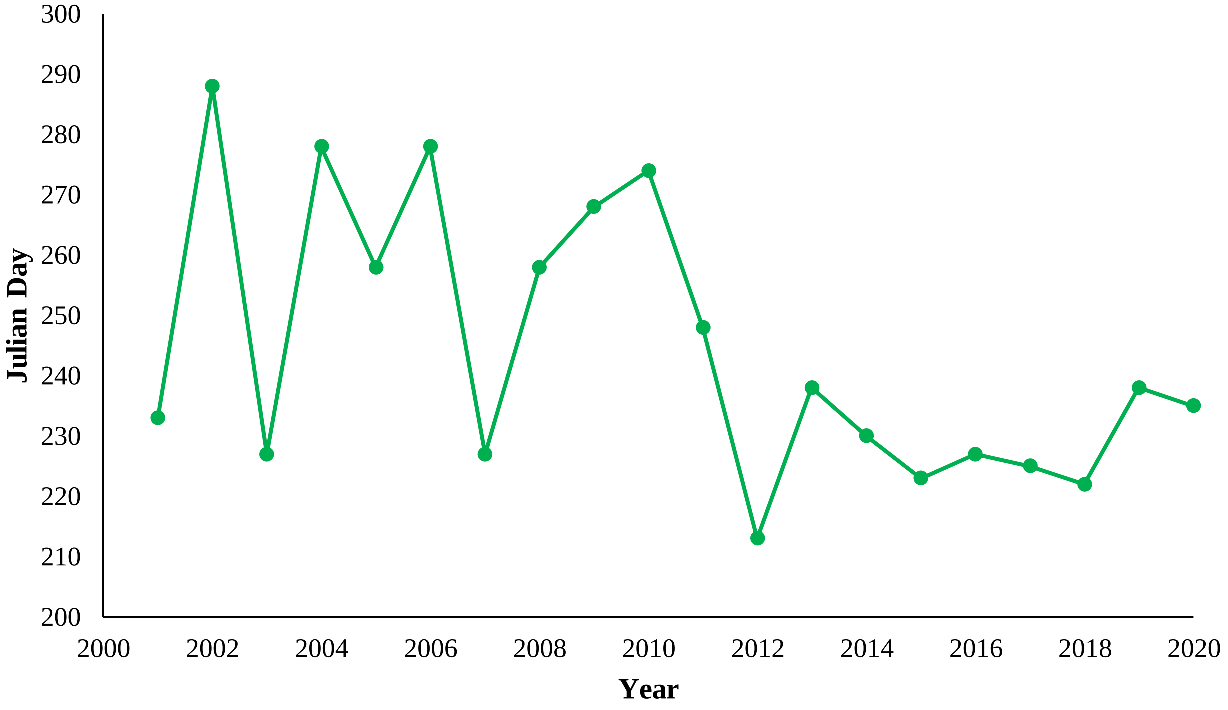


Figure 7 – Historic mean canola harvesting dates (2001-2020) for Alberta & the Peace River Region of British Columbia. Data from the Canadian Grain Commission (2022)

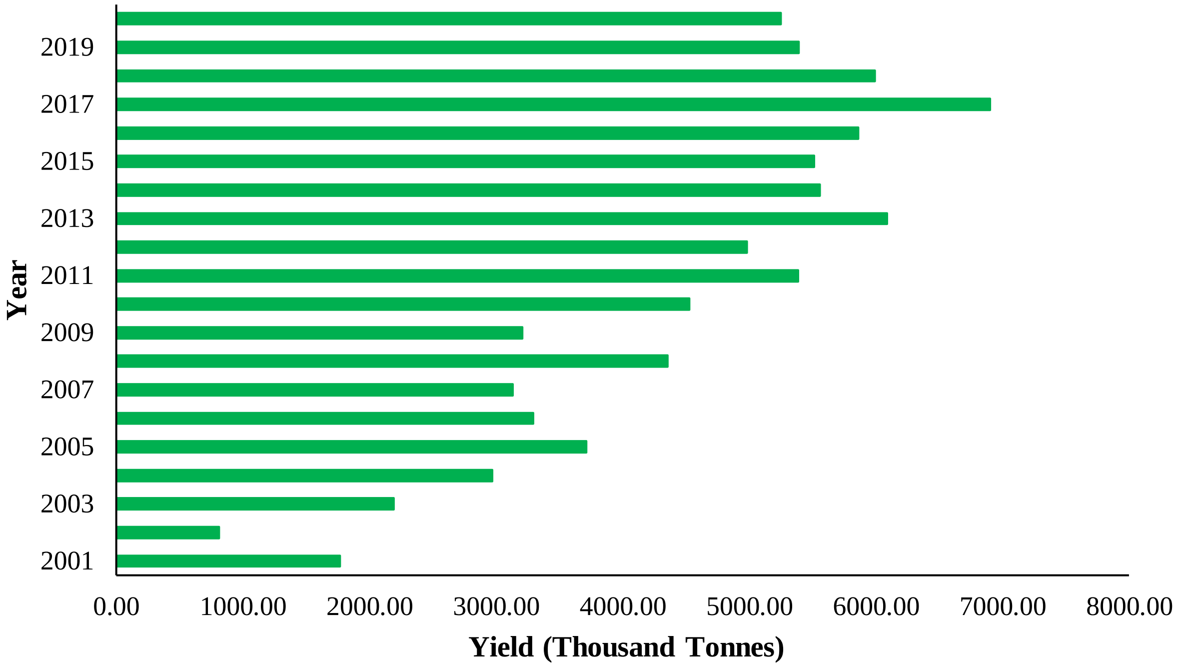


Figure 8 – Historic annual canola yield (2001-2020) for Alberta & the Peace River Region of British Columbia. Data from the Canadian Grain Commission (2022)

3.3 Climate Modelling Results

The modelled climate variables - for the period 2021-2040 – are taken from the ensemble means of the 13 selected climate models' outputs. The use of ensemble means ensures that the uncertainty between the models, and the uncertainty built into the modelling process, is addressed as fully as possible.

As displayed through figures 9 and 10, the individual models hold the same broad pattern, across the different SSPs, for both modelled temperature and precipitation respectively. This pattern projects increases to both mean annual temperatures and precipitation values under near future climate change. There is notable variability between the models themselves however, with ranges of 6.35, 6.25 and 6.83 °C in annual mean temperature and 153, 115 and 125 mm in annual mean precipitation across SSP1-2.6, SSP2-4.5 & SSP5-8.5 respectively for 2021.

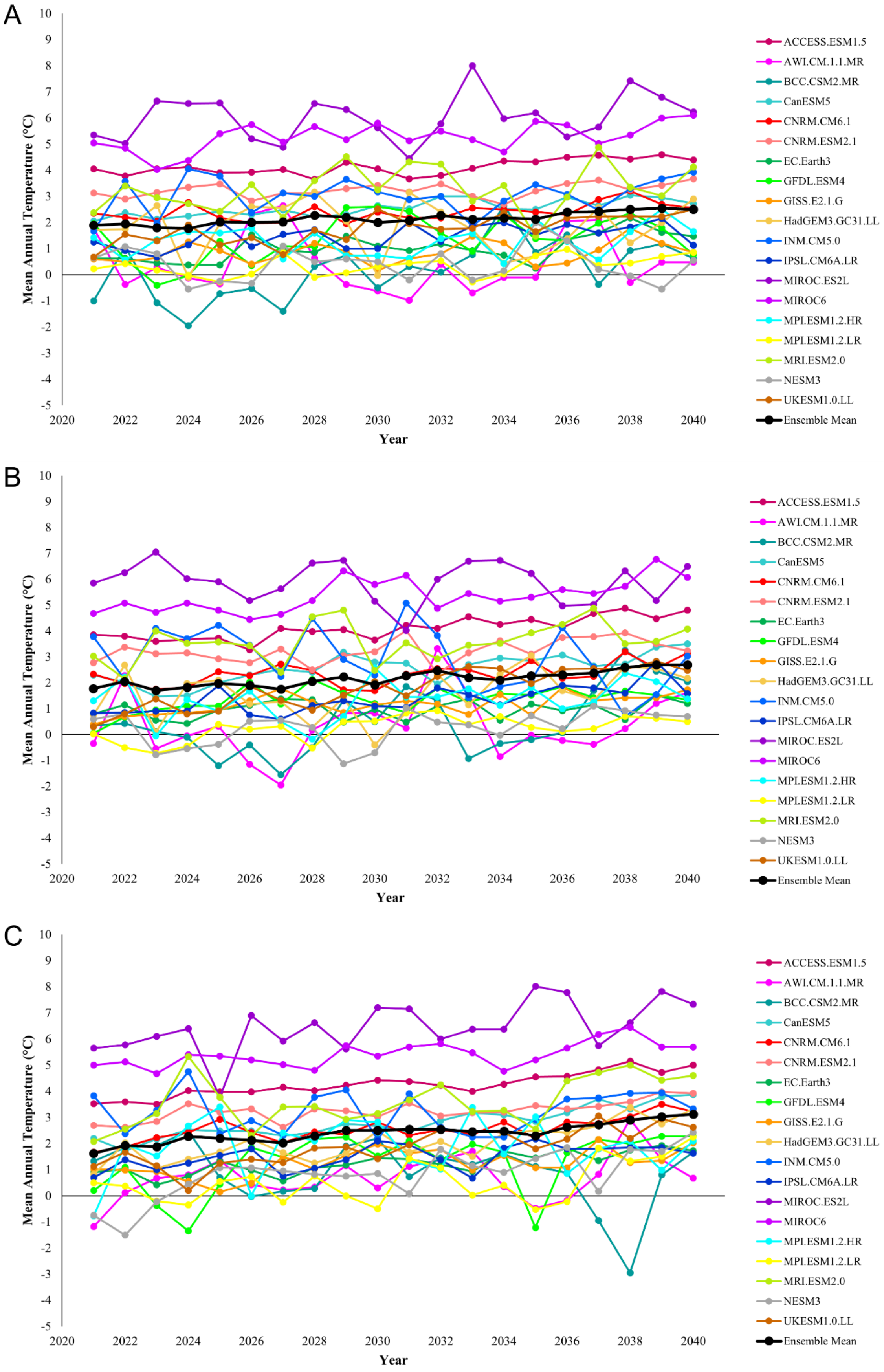


Figure 9 – Climate model ensemble of projected mean annual temperature, across British Columbia, under A) SSP1-2.6, B) SSP2-4.5, C) SSP5-8.5, for 2021-2040. Data from Mahony et al. (2022)

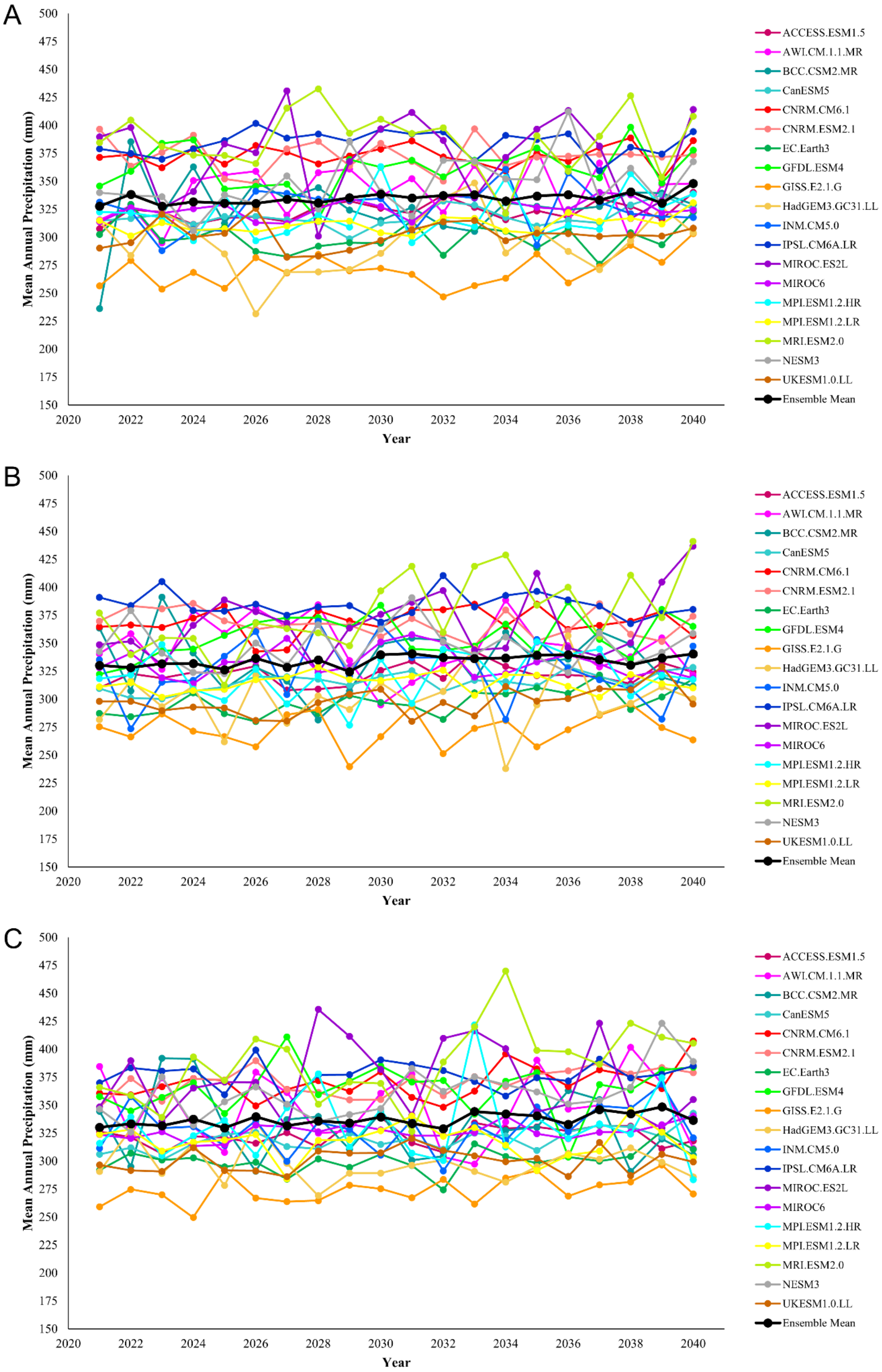


Figure 10 – Climate model ensemble of projected mean annual precipitation, across British Columbia, under A) SSP1-2.6, B) SSP2-4.5, C) SSP5-8.5, for 2021-2040. Data from Mahony et al. (2022)

3.4 Crop Modelling Results

The differences between modelled VWAD and biomass illustrates the impact of the differing SSPs on projected canola yield, with SSP1-2.6 and SSP2-4.5 featuring predominantly distinct increases to VWAD across the period at each case study site, with combined average increases of 20.14 and 29.30 kg/ha across the case study sites respectively – compared to modelled 2020 values. Comparatively, under SSP5-8.5 VWAD experiences a more mixed pattern across the period and between the case study sites – with the notable inclusion of negative percentage change in certain years – with a combined average increase of 11.89 kg/ha across the case study sites – compared to modelled 2020 values. Alternatively, modelled biomass more closely follows the pattern of temperature in relation to SSP projections, with mean average biomass change – in comparison to 2020 values - with biomass, like temperature, increasing across all years at each case study site with rising SSPs. Overall, the combined average increase to biomass across the case study sites for the period is 87.21, 86.10, 95.99 kg C/ha – under SSP1-2.6, SSP2-4.5 and SSP5-8.5 respectively – compared to modelled 2020 values.

Figure 11 highlights how the degree of increase in modelled biomass is seen to scale both with increasing SSP projections and time – at all case study locations. Whereas with VWAD (figure 12), the trends feature higher intra-annual variability - at each of the case study locations - specifically across the middle of the 20-year period, before stabilising into a general decreasing trend towards the end of the period – under all SSPs.

Additionally, figure 13 details the projected mean canola maturity dates for the future period, at each of the case studies and under the varying SSPs, from the CSM-CROPGRO-Canola model. Fort St. John displays the greatest variability between the SSPs, with a range of 9.25 days between the average maturity dates of the differing SSPs. Furthermore, projected maturity under SSP5-8.5 at Williams Lake is the overall earliest of all sites and projections – with a mean maturity date of 198.4 for the period.

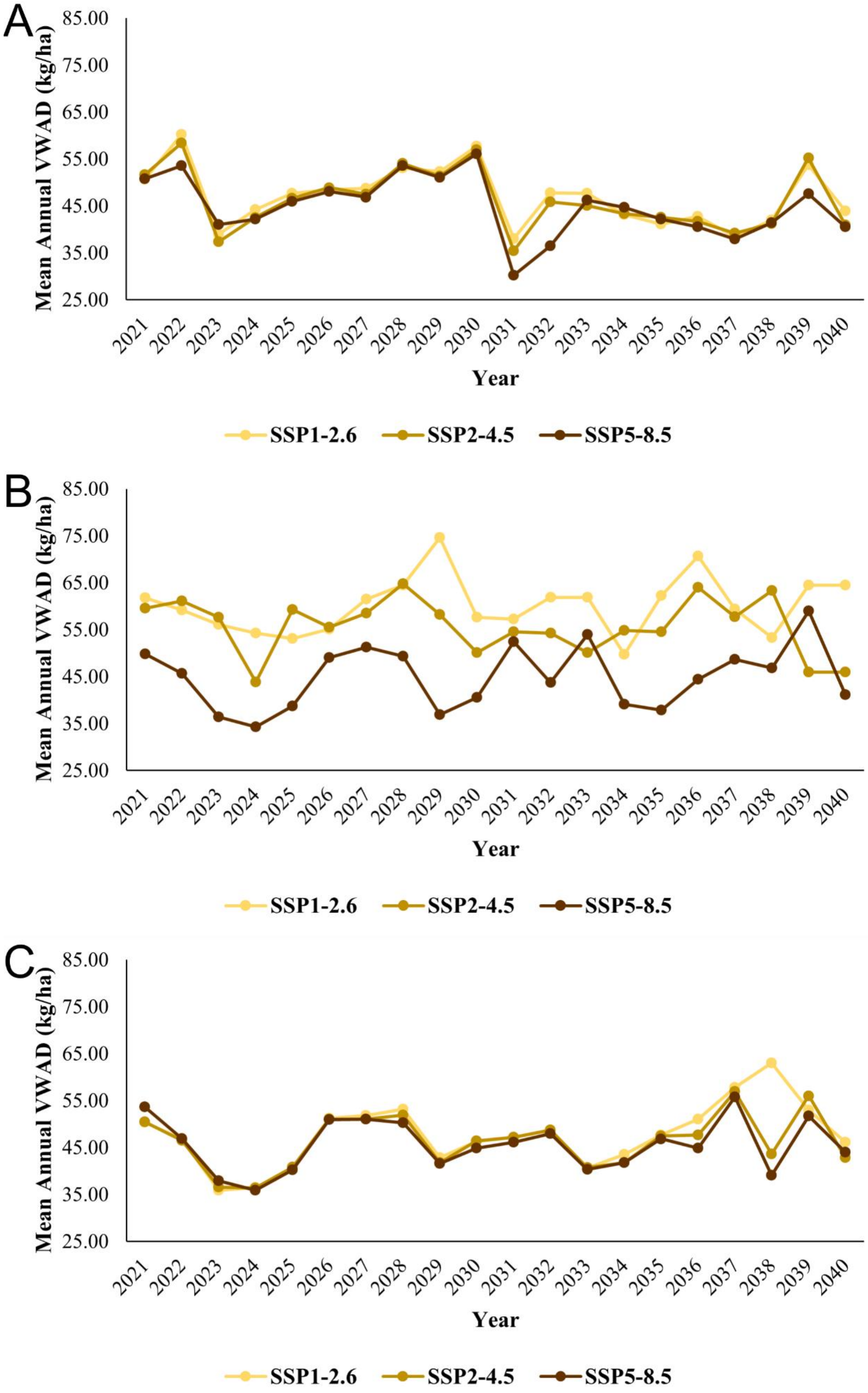


Figure 11 – The progression of projected mean annual VWAD from 2021 – 2040 at A) Williams Lake, B) Fort St. John, C) Fort Nelson, under the differing SSPs

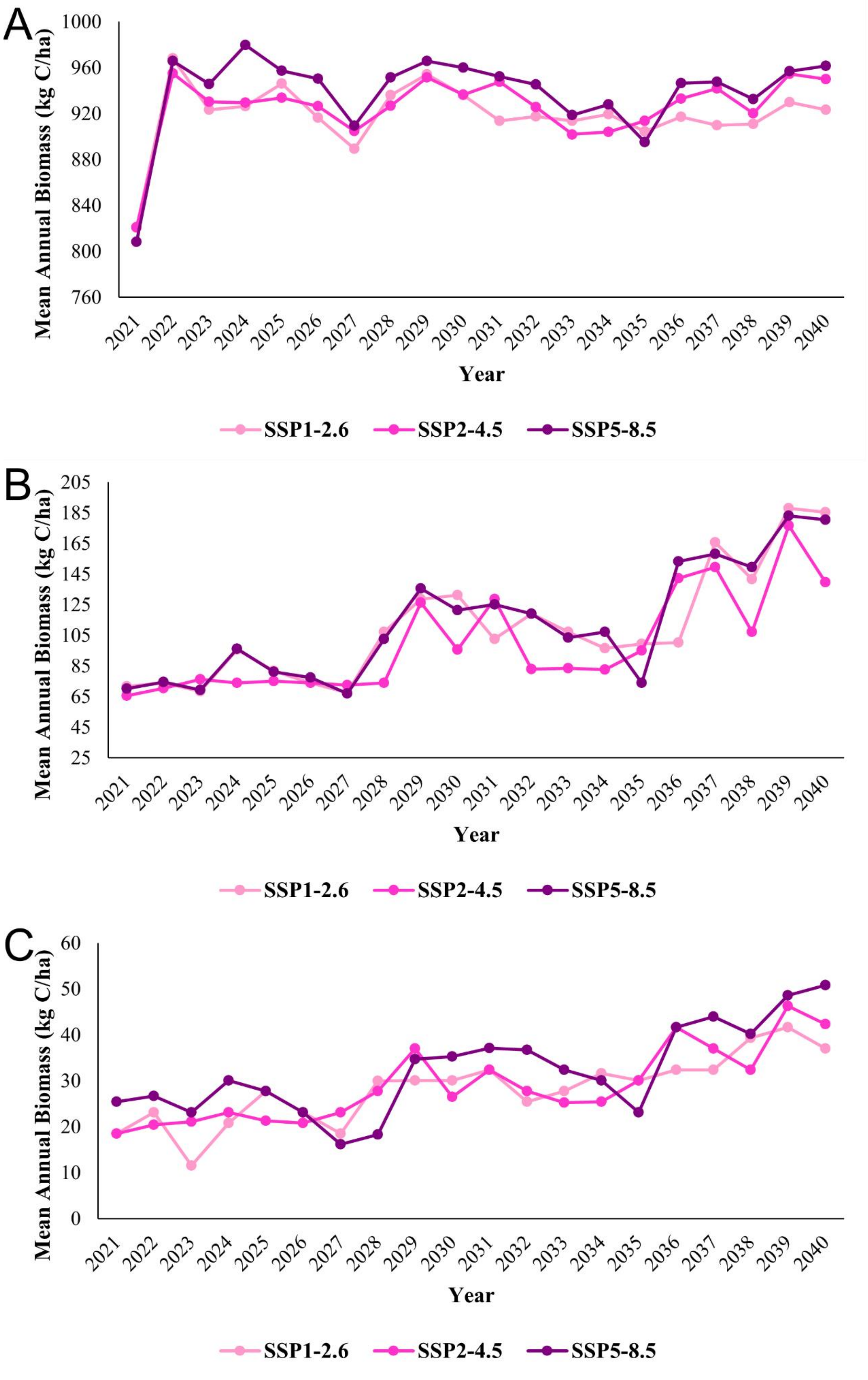


Figure 12 – The progression of projected mean annual biomass from 2021 – 2040 at A) Williams Lake, B) Fort St. John, C) Fort Nelson, under the differing SSPs

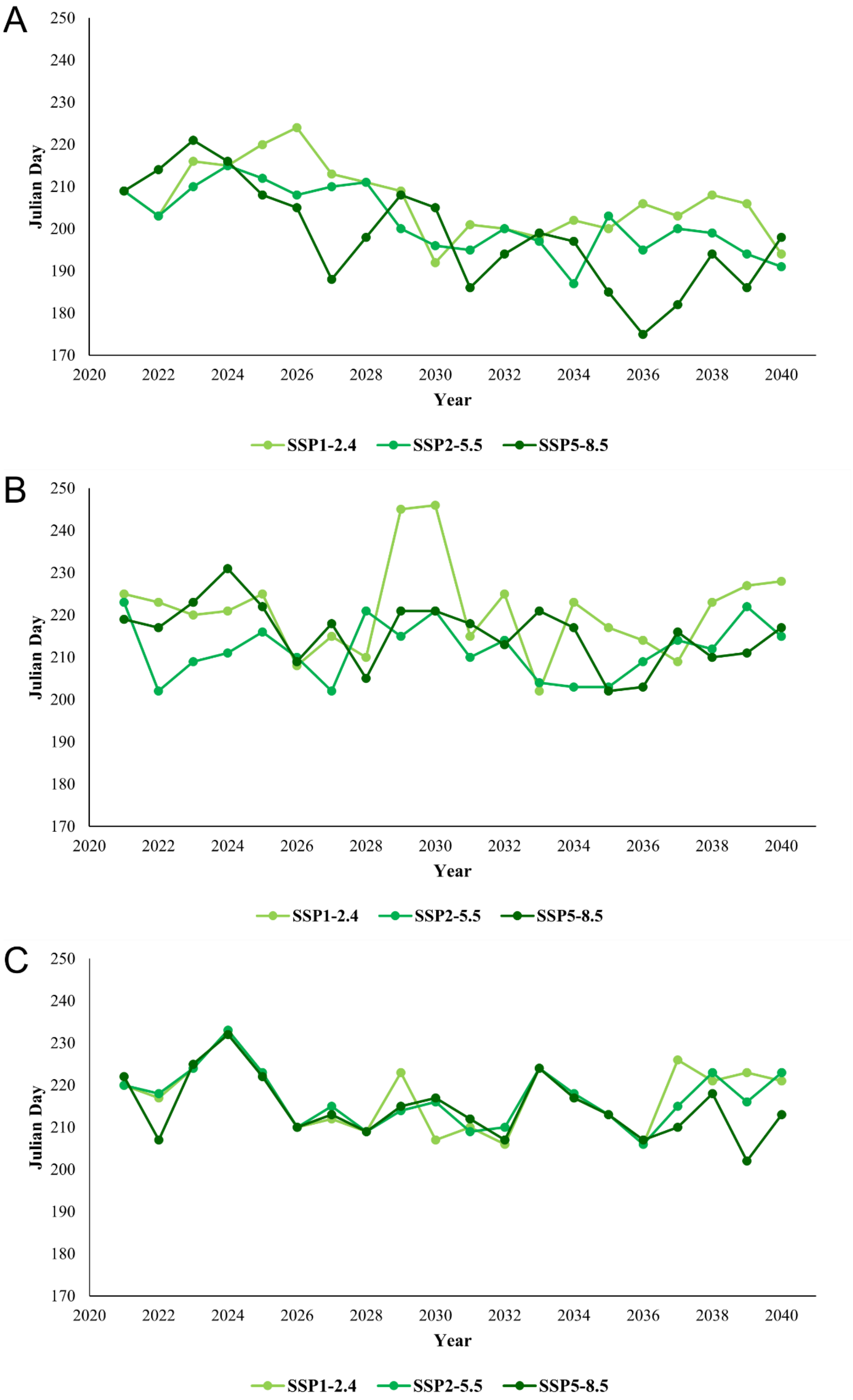


Figure 13 – Projected mean canola maturity date from the CSM-CROPGRO-Canola model for 2021-2040 at A) Williams Lake, B) Fort St. John, C) Fort Nelson, under the differing SSPs

3.5 Statistical Analysis

3.5.1 Z-Score Calculation for Outlier Identification

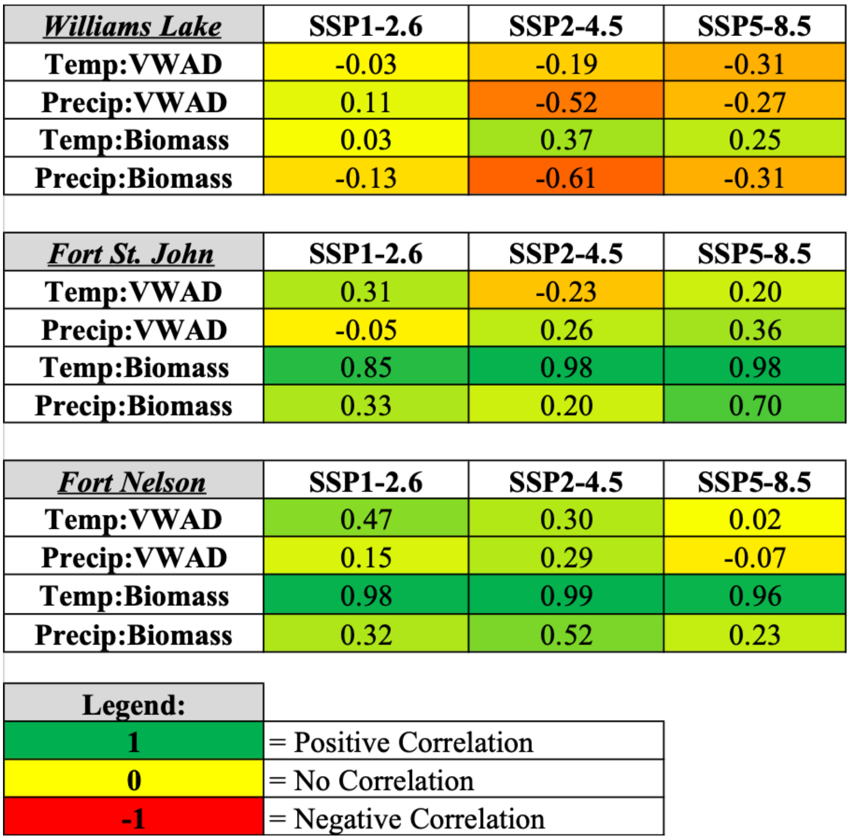
Across the modelled data a total of 6 outliers were identified by calculating Z-scores which fell below the 5% significance critical value. These included the biomass values for 2021 at Williams Lake under all SSPs, as well as the 2034 precipitation value under SSP1-2.6 and the 2021 and 2032 precipitation values under SSP5-8.5 for Fort St. John.

3.5.2 Kolmogorov-Smirnov Test

From the Kolmogrov-Smirnov test results, all variables, under all SSPs, at each case study site are identified to follow a pattern of normal distribution, for the study period - with all the maximal absolute differences being below the critical values at the 5% significance level.

3.5.3 Pearson Correlation Coefficient

The Pearson correlation coefficient values primarily illustrate the local variability between the case study sites – see figure 14. Significantly, both Fort Nelson and Fort St. John primarily feature positive correlations between temperature and precipitation against VWAD and biomass across each of the SSPs. Contrastingly, at Williams Lake a negative correlation is primarily recorded across the SSPs for temperature and precipitation against VWAD and biomass.



Williams Lake	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
Temp:VWAD	-0.03	-0.19	-0.31
Precip:VWAD	0.11	-0.52	-0.27
Temp:Biomass	0.03	0.37	0.25
Precip:Biomass	-0.13	-0.61	-0.31

Fort St. John	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
Temp:VWAD	0.31	-0.23	0.20
Precip:VWAD	-0.05	0.26	0.36
Temp:Biomass	0.85	0.98	0.98
Precip:Biomass	0.33	0.20	0.70

Fort Nelson	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
Temp:VWAD	0.47	0.30	0.02
Precip:VWAD	0.15	0.29	-0.07
Temp:Biomass	0.98	0.99	0.96
Precip:Biomass	0.32	0.52	0.23

Legend:	
🟩 **1**	= Positive Correlation
🟨 **0**	= No Correlation
🟥 **-1**	= Negative Correlation

Figure 14 – Pearson correlation coefficient values for the projected climate and canola variables, across the different case study sites

4. Discussion

4.1 The contrasting impacts of differing SSP based climate projections on forecast spring canola yield

Climate change in British Columbia, across the near future, is projected to result in both higher average temperatures and precipitation values, regardless of the SSP scenario. Despite the concurrence among SSPs on the overall trend of near future climate change, there is still considerable variation in the extent of the expected change between scenarios.

Explicitly, projected temperature values increase in agreement with the SSP scenarios, being highest under SSP5-8.5 at all three case study sites (figure 9). Comparatively mean annual precipitation is reduced under SSP2-4.5 – at all three case study sites – in comparison to both the SSP1-2.6 and SSP5-8.5 scenarios (figure 10). The observations highlight the complex relationship between temperature and precipitation. It has been observed that precipitation variability increases with rises in temperature – with greater warming increasing the occurrence of both wet and dry extremes (Zhang et al., 2021). Therefore, it can be inferred that SSP2-4.5 causes an overall reduction and destabilisation of rainfall patterns, while the level of increased warming that SSP5-8.5 represents - over SSP2-4.5 - generates a trend of more intense rainfall events.

Drought and heat stress have been observed to negatively impact canola growth and yield (Morrison and Stewart, 2002), resulting in the projected climate trends across British Columbia representing a major threat to the spring canola industry. The modelling results from the CSM-CROPGRO-Canola model emphasise the expected risk of decreased canola production, where projected VWAD levels decrease with increasing SSP projections – at all case study locations – being consistently lowest under SSP5-8.5 (refer to figure 11). These modelled results, from the CSM-CROPGRO-Canola model agree closely with a study on canola yield response to climate change across Canada, which reported that canola yield is projected to decrease by ~30% across the 21st century (Qian et al., 2018).

Contrastingly, the DNDC model projects increases to biomass with increasing levels of climate change. Across all three case study locations, it is projected that biomass will increase alongside increasing SSP projections, being the greatest under SSP5-8.5 (refer to figure 12). This projected behaviour is supported by Qian et al.'s study (2019), which specifically simulated spring canola yield under 1.5°C, 2°C, 2.5°C, and 3°C of warming above pre-industrial levels - with canola yield increasing under each warming level relative to the 2006-2015 baseline.

Therefore, the potential for canola yields to increase under near future projected climate change, before reaching a critical threshold beyond which yields decline, is highlighted (An and Carew, 2015), alongside, the differing sensitivities underlying different crop models, when comparing the DNDC and CSM-CROPGRO-Canola model outputs.

Regarding the differing sensitivities of the two models, Xu et al. (2021) observed that the yield outputs (including VWAD) from the CSM-CROPGRO-Canola model are most sensitive to parameters that affect the duration of critical growth periods, which include both temperature and water stress factors. Contrastingly, a study by Macharia et al. (2021) observed that the DNDC model both underestimated soil temperature and overestimated soil moisture. In the context of this study, these simulation inaccuracies lead to an underestimation of the effects of climate change on spring canola growth, which accounts for the discrepancy between the results of the two models.

4.2 The relationship between spring canola maturity, seeding and harvest dates, and different SSP based climate change projections

The historic trends of mean annual canola seeding and harvest dates – across the province – allows for valuable insight surrounding the relationship between climate conditions and maturity (figures 6 & 7). Specifically, the overall trends of both seeding and harvesting occurring earlier in the year, as the historic period progressed in line with both increasing mean-annual temperatures and precipitation levels. This is supported by Gan et al.'s 2004 study, which details that increased temperatures specifically lead to a reduced growing period, due to accelerated plant development, yet also reduced yield potential.

This is further supported by the modelled maturity outputs from the CSM-CROPGRO-Canola model. Figure 13 displays trends of accelerating spring canola maturity rates - both over time and under increasing SSP projections. Furthermore, Qian et al.'s 2018 study, using the CSM-CROPGRO-Canola model in conjunction with Representative Concentration Pathways, likewise projected decreases to the spring canola growing period across Canada, of up to 9 days, in the context of projected temperature increases. Additionally, following the observations regarding the yield outputs from the CSM-CROPGRO-Canola model, Xu et al.'s 2021 study concludes that maturity date is also mainly controlled by parameters which impact the length of critical growth periods – which include both temperature and water stress.

Overall, near future climate change trends across British Columbia are projected to markedly decrease the overall growing period of spring canola. This subsequently carries significant implications surrounding agricultural planning, with mean annual seeding and harvest dates expected to occur earlier in the year – to adapt to the warmer and wetter winter and spring conditions (Qian et al., 2018). This in turn, will impact crop management decisions – including adjusting the planting of cover crops, alongside pesticide and fertiliser applications, in accordance with the new growing period.

4.3 Which areas of current spring canola production in British Columbia are most threatened by climate change?

The patterns of near future climate change, across British Columbia, are highly varied on a spatial scale. Based on the observed relationships between temperature and precipitation with canola yield, regions projected to experience the largest temperature increases and the greatest reductions in precipitation are likely to be the most vulnerable to near future climate change in terms of spring canola production.

Specifically the South of British Columbia is projected to experience both the greatest increases to temperature and precipitation. Resultantly, it can be expected that canola production in the South of the province will be most threatened across the near future. The area initially experiences periods of increased yield – benefitting from the increased temperatures and precipitation - before temperatures surpass a critical threshold and limits yields due to heat stress (An and Carew, 2015), while increased precipitation begins to harm yields by causing waterlogging (Ploschuk et al., 2020).

These conclusions are supported by the prior case study level observations, whereby Williams Lake – located in the South of British Columbia – is projected to experience the second smallest average increases to canola VWAD under the CSM-CROPGRO-Canola model and the smallest average increases to canola biomass under the DNDC model – under each of the SSPs, across 2021-2040, against the 2020 baseline (figures 11 & 12). Whereas Fort Nelson – located in the North of the province – is projected to experience the greatest average increases in canola VWAD, under the CSM-CROPGRO-Canola model and the greatest average increases to canola biomass under the DNDC model – under each of the SSPs, across 2021-2040, against the 2020 baseline (figures 11 & 12).

5. Conclusion

The analysis of British Columbia's climate trends from 2001-2020 underscores the positive correlation between warming temperatures, increased precipitation, and canola yields. Historic patterns align with accelerated spring canola maturity, showcasing the influence of climate on growth. Looking ahead, CMIP6 models project a continuation of these trends over the next two decades, with observable connections to rising greenhouse gas emissions in different SSP scenarios.

Modelling exercises, employing CSM-CROPGRO-Canola and DNDC, echo the CMIP6 model projections, pointing to a notable decline in future spring canola production due to climate change. A critical warming threshold is identified, signaling initial yield improvements followed by increased heat and water stress limiting crop growth. Reductions in production correlate with rising SSP scenarios, particularly SSP5-8.5. Spatial variability becomes apparent, with the South anticipated to face more adverse conditions compared to the North by the end of the modelled period. As a strategic response, relocating canola production to the North emerges as a pivotal approach for enhancing the long-term viability of spring canola cultivation in British Columbia.

Conflict of interest statement

The author declares that they have no conflicting interests.

References

Aggarwal, P., Vyas, S., Thornton, P. and Campbell, B.M., 2019. How much does climate change add to the challenge of feeding the planet this century? *Environmental Research Letters*, 14(4), 043001. https://doi.org/10.1088/1748-9326/aafa3e.

Allen, M., 2017. The SAGE encyclopedia of communication research methods. *The SAGE Encyclopedia of Communication Research Methods*, 4. https://doi.org/10.4135/9781483381411.

An, H. and Carew, R., 2015. Effect of climate change and use of improved varieties on barley and canola yield in Manitoba. *Canadian Journal of Plant Science*, 95(1), 127–139. https://doi.org/10.4141/cjps-2014-221.

Angadi, S.V., Cutforth, H.W., McConkey, B.G. and Gan, Y., 2003. Yield Adjustment by Canola Grown at Different Plant Populations under Semiarid Conditions. *Crop Science*, 43(4), 1358–1366. https://doi.org/10.2135/cropsci2003.1358.

Androkovich, R., Desjardins, I., Tarzwell, G. and Tsigaris, P., 2008. Land Preservation in British Columbia: An Empirical Analysis of the Factors Underlying Public Support and Willingness to Pay. *Journal of Agricultural and Applied Economics*, 40(3), 9991013. https://doi.org/10.1017/S1074070800002479.

Ball, M., 2022. Modelling the historic and projected near-surface temperature trends across Canada. *Geography*, 107(3), 158–165. https://doi.org/10.1080/00167487.2022.2114169.

Barthet, V., 2016. Comparison between Canadian Canola Harvest and Export Surveys. *Plants*, 5(3), 30. https://doi.org/10.3390/plants5030030.

Bayer Crop Science., 2021. Simple Guidelines to Improve your Canola Planting. https://www.cropscience.bayer.us/learning-center/articles/Simple-guidelines-to-improve-your-canola-planting.

Canada Grain Commission., 2022. Scientific analysis of western Canadian canola harvest and export quality. https://grainscanada.gc.ca/en/grain-research/export-quality/oilseeds/canola/.

Daun, J.K., 2011. Chapter 1 - Origin, Distribution, and Production. In: J.K. Daun, N.A. Michael Eskin and D. Hickling, eds., *Canola: Chemistry, Production, Processing, and Utilization*. AOCS Press, 1–27.:https://doi.org/10.1016/B978-0-9818936-5-5.50005-X.

Canadian Society of Soil Science., 2020. Luvisolic - Soils of Canada. https://soilsofcanada.ca/orders/luvisolic.php.

Canola Digest., 2017. Optimum row spacing depends on many factors, including weeds. https://canoladigest.ca/science-edition-2017/optimum-row-spacing-depends-on-many-factors-including-weeds/.

Gan, Y., Angadi, S.V., Cutforth, H., Potts, D., Angadi, V.V. and McDonald, C.L., 2004. Canola and mustard response to short periods of temperature and water stress at different developmental stages. *Canadian Journal of Plant Science*, 84(3), 697–704. https://doi.org/10.4141/p03-109.

Geng, S., Auburn, J., Brandstetter, E. and Li, B., 1988. A program to simulate meteorological variables: documentation for SIMMETEO. *Agronomy Progress Rep*, 204.

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K. and Wiltshire, A., 2010. Implications of climate change for agricultural productivity in the early twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554), 2973–2989. https://doi.org/10.1098/rstb.2010.0158.

Government of British Columbia., 2021. Grains & Oilseeds. https://www2.gov.bc.ca/gov/content/industry/agriculture-seafood/animals-and-crops/crop-production/grains-oilseeds-pulse-crops.

Greenland, S., Senn, S.J., Rothman, K.J., Carlin, J.B., Poole, C., Goodman, S.N. and Altman, D.G., 2016. Statistical tests, P values, confidence intervals, and power: a guide to misinterpretations. *European Journal of Epidemiology*, 31(4), 337–350. https://doi.org/10.1007/s10654-016-0149-3.

He, W., Yang, J.Y., Drury, C.F., Smith, W.N., Grant, B.B., He, P., Qian, B., Zhou, W. and Hoogenboom, G., 2018. Estimating the impacts of climate change on crop yields and N2O emissions for conventional and no-tillage in Southwestern Ontario, Canada. *Agricultural Systems*, 159, 187–198. https://doi.org/10.1016/j.agsy.2017.01.025.

Jannat, A., Ishikawa-Ishiwata, Y. and Furuya, J., 2022. Does Climate Change Affect Rapeseed Production in Exporting and Importing Countries? Evidence from Market Dynamics Syntheses. *Sustainability*, 14(10), 6051. https://doi.org/10.3390/su14106051.

Jing, Q., Shang, J., Qian, B., Hoogenboom, G., Huffman, T., Liu, J., Ma, B.-L., Geng, X., Jiao, X., Kovacs, J. and Walters, D., 2016. Evaluation of the CSM-CROPGRO-Canola Model for Simulating Canola Growth and Yield at West Nipissing in Eastern Canada. *Agronomy Journal*, 108(2), 575–584. https://doi.org/10.2134/agronj2015.0401.

Kutcher, H.R., Warland, J.S. and Brandt, S.A.,2010. Temperature and precipitation effects on canola yields in Saskatchewan, Canada. *Agricultural and Forest Meteorology*, 150(2), 161–165. https://doi.org/10.1016/j.agrformet.2009.09.011.

Liang-Liang, L., Jian, L. and Ru-Cong, Y., 2021. Evaluation of CMIP6 HighResMIP models in simulating precipitation over Central Asia. *Advances in Climate Change Research*. https://doi.org/10.1016/j.accre.2021.09.009.

Liu, H., Chen, C., Li, Y., Duan, Z. and Li, Y., 2022. Characteristic and correlation analysis of metro loads. *Smart Metro Station Systems*, 237–267. https://doi.org/10.1016/b978-0-323-90588-6.00009-3.

Macharia, J.M., Ngetich, F.K. and Shisanya, C.A., 2021) Parameterization, calibration and validation of the DNDC model for carbon dioxide, nitrous oxide and maize crop performance estimation in East Africa. *Heliyon*, 7(5), e06977. https://doi.org/10.1016/j.heliyon.2021.e06977.

Mahony, C.R., Wang, T., Hamann, A. and Cannon, A.J.,2022. A global climate model ensemble for downscaled monthly climate normals over North America. *International Journal of Climatology*, 42(11), 5871–5891. https://doi.org/10.1002/joc.7566.

Massey, F.J.,1951. The Kolmogorov-Smirnov Test for Goodness of Fit. *Journal of the American Statistical Association*, 46(253), 68–78. https://doi.org/10.2307/2280095.

Meinshausen, M., Nicholls, Z.R.J., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J.G., Daniel, J.S., John, A., Krummel, P.B., Luderer, G., Meinshausen, N., Montzka, S.A., Rayner, P.J., Reimann, S. and Smith, S.J., 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, 13(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020.

Morrison, M.J. and Stewart, D.W., 2002. Heat Stress during Flowering in Summer Brassica. *Crop Science*, 42(3), 797–803. https://doi.org/10.2135/cropsci2002.7970.

National Centers for Environmental Information., 2021. Global Historical Climatology Network daily (GHCNd). https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily.

Page, E.R., Meloche, S., Moran, M., Caldbeck, B. and Barthet, V., 2021. Effect of seeding date on winter canola (Brassica napus L.) yield and oil quality in southern Ontario. *Canadian Journal of Plant Science*, 101(4), 490–499. https://doi.org/10.1139/cjps-2020-0220.

Peace River Regional District., 2014. Regional Agricultural Plan: Background Report. https://prrd.bc.ca/wp-content/uploads/Background-Report-Final-November-2014.pdf.

Perez, L., A. Nelson, T., Bourbonnais, M. and Ostry, A., 2015. Modelling the Potential Impact of Climate Change on Agricultural Production in the Province of British Columbia. *Energy and Environment Research*, 5(1). https://doi.org/10.5539/eer.v5n1p49.

Pickering, N.B., Hansen, J.W., Jones, J.W., Wells, C.M., Chan, V.K. and Godwin, D.C.,1994. WeatherMan: A Utility for Managing and Generating Daily Weather Data. *Agronomy Journal*, 86(2), 332–337. https://doi.org/10.2134/agronj1994.00021962008600020023x.

Ploschuk, R.A., Miralles, D.J., Colmer, T.D. and Striker, G.G.,2020. Waterlogging differentially affects yield and its components in wheat, barley, rapeseed and field pea depending on the timing of occurrence. *Journal of Agronomy and Crop Science*, 206(3), 363–375. https://doi.org/10.1111/jac.12396.

Qian, B., Jing, Q., Bélanger, G., Shang, J., Huffman, T., Liu, J. and Hoogenboom, G., 2018. Simulated Canola Yield Responses to Climate Change and Adaptation in Canada. *Agronomy Journal*, 110(1), 133–146. https://doi.org/10.2134/agronj2017.02.0076.

Qian, B., Zhang, X., Smith, W., Grant, B., Jing, Q., Cannon, A.J., Neilsen, D., McConkey, B., Li, G., Bonsal, B., Wan, H., Xue, L. and Zhao, J., 2019. Climate change impacts on Canadian yields of spring wheat, canola and maize for global warming levels of 1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C. *Environmental Research Letters*, 14(7), 074005. https://doi.org/10.1088/1748-9326/ab17fb.

RealAgriculture., 2017. Bayer retiring InVigor 5440 and L130 canola varieties. https://www.realagriculture.com/2017/08/bayer-retiring-invigor-5440-and-l130-canola-varieties/.

Richardson, C.W. and Wright, D.A., 1984. WGEN: A model for generating daily weather variables. ARS (USA).

Schober, P., Boer, C. and Schwarte, L.A., 2018. Correlation Coefficients: Appropriate Use and Interpretation. *Anesthesia & Analgesia*, 126(5), 1763–1768. https://doi.org/10.1213/ane.0000000000002864.

van Vuuren, D.P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S., KC, S., Kriegler, E. and O'Neill, B., 2017. The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Global Environmental Change*, 42, 148–152. https://doi.org/10.1016/j.gloenvcha.2016.10.009.

Wanasundara, J.P.D., Tan, S., Alashi, A.M., Pudel, F., Blanchard, C., 2017. Proteins From Canola/Rapeseed, in: Sustainable Protein Sources. (p. 285–304). Elsevier, https://doi.org/10.1016/B978-0-12-802778-3.00018-4

Wang, T., Hamann, A., Spittlehouse, D. and Carroll, C., 2016. Locally Downscaled and Spatially Customizable Climate Data for Historical and Future Periods for North America. *PLOS ONE*, 11(6), p.e0156720. https://doi.org/10.1371/journal.pone.0156720.

Wang, Y., Sarkar, A., Hasan, A.K., Tian, Y., Wu, Q., Hossain, M.S. and Wei, F., 2022. The Evaluation of Temporal and Spatial Trends of Global Warming and Extreme Ocean Surface Temperatures: A Case Study of Canada. *ISPRS International Journal of Geo-Information*, 11(1), 21. https://doi.org/10.3390/ijgi11010021.

Williams, B., Halloin, C., Löbel, W., Finklea, F., Lipke, E., Zweigerdt, R. and Cremaschi, S., 2020. Data-Driven Model Development for Cardiomyocyte Production Experimental Failure Prediction. *Computer Aided Chemical Engineering*, 1639–1644. doi:10.1016/b978-0-12-823377-1.50274-3.

Xu, M., Wang, C., Ling, L., Batchelor, W.D., Zhang, J. and Kuai, J., 2021. Sensitivity analysis of the CROPGRO-Canola model in China: A case study for rapeseed. *PLOS ONE*, 16(11), e0259929. https://doi.org/10.1371/journal.pone.0286176.

Zhang, W., Furtado, K., Wu, P., Zhou, T., Chadwick, R., Marzin, C., Rostron, J. and Sexton, D., 2021. Increasing precipitation variability on daily-to-multiyear time scales in a warmer world. *Science Advances*, 7(31). https://doi.org/10.1126/sciadv.abf8021.