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Performance of current canola (*Brassica napus*) hybrids under future rainfed production management

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ABSTRACT

Canola is vulnerable to the current changing weather conditions, mainly due to moisture and temperature-related stresses. Adaptation strategies such as shifting planting dates allow producers to improve canola's response to environmental conditions. This study aims to explore the optimal setting to increase canola productivity within the Canadian Prairies under future scenarios from the Shared Socioeconomic Pathways. Hence, we define the optimal planting period to avoid water and temperature stresses as well as the optimal nitrogen (N) concentration in fertilization to maximize canola productivity. We used DSSAT-Pythia to simulate four canola hybrids, 24 planting dates, five nitrogen concentrations, and four future climate scenarios, with a spatial resolution of $0.25^\circ \times 0.25^\circ$ in the Canadian Prairies. The model's performance showed satisfactory predictions of canola phenology and grain yield for all hybrids. On spatial and temporal averages, the second hybrid showed highest yield values, with most values between 2500 and 3000 kg ha^{-1}. In addition, spatial analysis shows that the first hybrid can complete the crop cycle in all growing zones when planted early (April), and the second and third hybrids completed the cycle when planted later (June and July). Nitrogen uptake was affected by weather conditions. The higher the temperature, especially during the bolting stage, the less nitrogen uptake from the plant. Fertilization with high N concentration (200 kg ha^{-1}) is expected to be more effective before May 19 under very hot scenarios and before June 08 under mild temperatures. Overall, canola yield increased with an increase in N concentration.

1. Introduction

Climate variability poses a significant threat to canola (*Brassica napus L.*) production in Canada, primarily through alterations in temperature regimes and hydrological cycles. Increasing frequency and intensity of extreme temperature events [1] have disrupted river streamflow and snowmelt dynamics [2], thereby affecting soil moisture levels and irrigation potential. These changes exacerbate water and heat stress in crops, leading to elevated evapotranspiration rates and increased water demand [3]. Soil water deficits are among the most critical constraints to crop productivity, often resulting in substantial yield reductions [4]. Moreover, the prevalence of extreme cold events in Canada surpasses that of extreme heat [1]. Low temperatures adversely affect canola development by prolonging the accumulation of growing degree days required for optimal yield formation [5]. Frost stress during early developmental stages can inhibit or delay seed germination and is lethal to seedlings and non-acclimated plants during flowering and grain-filling phases. Exposure to frost during these sensitive periods can damage reproductive structures such as silique embryos and ovules, leading to increased rates of abortion, infertility, and ultimately reduced grain yield [6,7]. Besides, early frosts are more frequent in the Canadian Prairie Region, where the season starts late because of lower temperatures in the spring that end during fall [8].

Drought [9], heat wave [10, p. 2], and frost [8] events harm primary

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agriculture, compromising crops' productivity [11]. Projections of crop production under extreme events from crop models help recommend climate-smart adaptations. Crop models are interdisciplinary and focus on soil-water-plant-atmosphere interactions. The Decision Support System for Agrotechnology Transfer (DSSAT) is used globally to simulate soil-plant-water-atmosphere interactions for more than 40 crops in mono or intercropping systems [12,13]. Diverse studies have used DSSAT to evaluate water availability and its use efficiency, the effects of temperature variability, nitrogen fertilization and use efficiency, and the yield gap [14]. However, recent studies regarding canola have still used InVigor® 5440 based on older field experiments [15,16] or to simulate production with DSSAT [17–19]. InVigor® 5440 was a hybrid that dominated the industry for over ten years but has been retired since 2017 after better-suited hybrids were developed [20]. Despite the widespread use of crop models to simulate canola production, most rely on outdated genetic information from cultivars no longer available on the market. This creates a significant gap in accurately predicting canola performance under current and future climate conditions, especially given the genetic advancements in modern cultivars. Using crop models with appropriate data can promote environmental preservation and solve agroecosystem inquiries like crop production and availability [21]. Further, predicting extreme and high-impact events on canola production is a first step to mitigating the impacts.

Projections using the Shared Socio-economic Pathways (SSPs) climate scenarios with rising temperatures from the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) [22] allow us to account for future variability. A rise of 1 $^{\circ}C$ in the air temperature can advance the proper planting date from three to six days [23]. Optimizing the planting date enables agricultural producers to mitigate the risk of early-season frost, which can cause significant damage or mortality to seedlings, and to avoid exposure to high-temperature stress during the flowering phase, which adversely affects grain development and filling. With optimal planting dates, the plants compete more efficiently with weeds for water and nutrients and improve grain production [7]. Besides, effective nitrogen management is essential for sustainable production. Nitrogen is a costly input for farmers, and its loss to the ecosystem contributes to contamination. Studies show a rise in canola yield when applying 150 or 200 kg ha^{-1} of nitrogen. However, canola's response to nitrogen depends on the environmental conditions [24].

Under future climate scenarios projected by CMIP6 and SSPs, optimizing planting dates and nitrogen application rates will enhance rainfed canola yield and resilience in the Canadian Prairie Region. This improvement is expected through mitigation of temperature and water stress and increased resource use efficiency. Consequently, this study aims to find the optimum rainfed canola production in the Canadian Prairie Region under various future climate scenarios using the DSSAT-Pythia agricultural model. Specifically, the objectives are (1) to evaluate the most resilient hybrid among four new hybrids, (2) to define the optimal planting period to avoid water and temperature stresses, and (3) to identify the optimal nitrogen concentration in fertilization. The findings of this study should allow producers and shareholders to (re) adapt their practices and effectively mitigate the impacts of climate change on canola production in the region.

1.1. *Study site*

The study site is the Canadian Prairie Region in Alberta, Manitoba, and Saskatchewan (Fig. 1). These provinces are in the western part of the country. The region of interest is part of the Interior Plains [25]. It has a standard continental climate, with freezing winters with minimum temperatures reaching below −40 °C and hot summers above 40 °C [26,27]. This region is also characterized by its semi-arid state, comparable to 10 % of the West Coast's annual mean precipitation [28], forming the country's largest dryland, where short and long-term droughts naturally occur throughout the year [25]. Historical observations have shown a variation in temperature of 1.9 °C and 7 % of annual precipitation in the Prairie Provinces from 1948 to 2016, with an adverse change in precipitation during winter [28]. This variability in climate affects ecosystems and the distribution of local flora and fauna [27], which could directly impact canola.

Despite its semi-arid climate and extreme temperatures, the Prairie Region thrives in primary agriculture and has significantly contributed to the Canadian economy. More than 500,000 people were employed by primary agriculture in Canada in 2023 [29]. Of the 62.2 million hectares of farmland in Canada, 47.5 % are in the Prairie Provinces, of which 20 % cultivate oilseed excluding soybeans [29,30]. Canola is one of the most important crops in Canadian agriculture and the economy. On average, canola has promoted the highest crop commodity farm cash

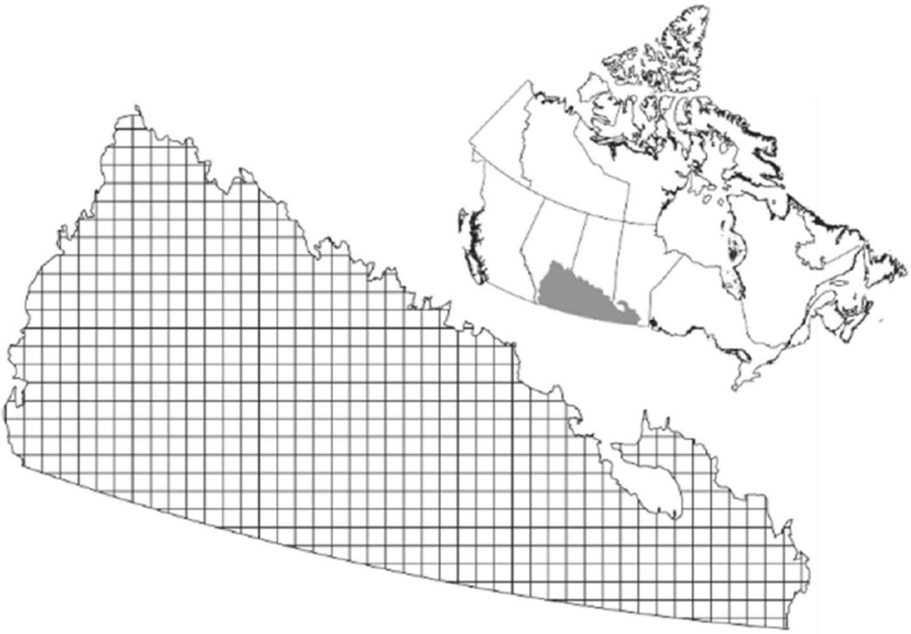

Fig. 1. The study region where the simulations were applied. The Canadian Prairie Region is represented as the grey area on the map of Canada and in the zoomed-in area with grid cells at 0.25° × 0.25°.

receipts in Saskatchewan and Manitoba from 2019 to 2023 [29]. Canola production has positively impacted the agriculture and agri-food sectors, promoting great growth potential for the Canadian economy [29, 31]. However, climate change and extreme temperatures may intensively affect its production, directly impacting the vegetable oil, feedstock, and biofuel industries [32].

2. Methods

2.1. Decision support system for Agrotechnology Transfer (DSSAT) and input data

DSSAT is a software application that integrates crop models and assesses management and climate scenarios using modules to simulate crop physiology and productivity by evaluating soil-water-plant-atmosphere dynamics and management conditions at the field level. This system has a user-friendly interface, which facilitates multiple module usage for diverse applications [12]. However, handling big, gridded data within the DSSAT interface is not computationally feasible given the experiments that were employed to explore multiple hybrids, planting dates, nitrogen concentrations, and climate change scenarios. Accordingly, the crop simulation model (CSM-CROPGRO-Canola) in DSSAT had to be integrated with Python (i.e., programming software) through a framework named DSSAT-Pythia to simulate the gridded data and produce spatial fields. DSSAT-Pythia treats each grid cell independently in each simulation. Climate data are spatially matched to each soil grid cell using the nearest-neighbor technique [33]. In this spatial overlay approach, each simulation integrates localized soil characteristics with the most representative climate conditions available.

To conduct a simulation, the minimum input data include daily weather records, detailed crop and soil properties, and site-specific field management practices. DSSAT can be more accurate than other crop models as it is more sensitive to climate input [34]. Yet only crop and soil data are required to calibrate and evaluate the model [12]. The model calibration and validation process followed the steps described by Ahmed et al. and Asgari et al. [35,36], focusing on phenological development and seed content. Although InVigor®5440 is already calibrated and widely used in CSM-CROPGRO-Canola simulations, it is no longer sold in Canada [20]. Hence, four canola hybrids (InVigor®-L233P, InVigor®-L340PC, InVigor®-L343PC, and InVigor®-L350PC) were calibrated and included in the crop model to be simulated in this study, aiming to offer up-to-date results to canola growers and shareholders. We used the Generalized Likelihood Uncertainty Estimation (GLUE) and the Genetic Coefficient Calculator (GENCALC) tools available in DSSAT to calibrate the genetic parameters for each hybrid. Since detailed data from InVigor cultivar trials conducted in the Canadian Prairie region are proprietary and managed by private companies, the datasets are confidential and are not publicly accessible. This resulted in the limitation of phenological and productivity data of InVigor cultivars in Canada, so we opted for using an analog method. For this, we have followed a common practice among crop modellers as stated by Seidel et al. (2018) [37]. Therefore, we utilized the observed data of Canopy Height (m), Anthesis Date (DAP), Grain Oil Content (%), Physiological Maturity (DAP), and Yield (kg ha^{-1}) from the 2022 variety trials in Langdon, ND, from the North Dakota State University [38] to calibrate the genetic parameters. Afterward, we validated the model with observed data from the 2020 to 2024 variety trials in Langdon [39], and Conrad, Havre and Kalispell, MT in 2023 [40]. Observed data for InVigor®-L343PC, and InVigor®-L350PC are available from 2022, according to their later release to the market. The model performance was evaluated by comparing observed and simulated data with the correlation coefficient (R^2), the normalized root mean squared error (nRMSE), and the index of agreement (d), broadly applied by the scientific community [36].

The soil dataset [41,42] has a 10-km grid cell spatial resolution. It derives from the databases of SoilGrids (1 km) and ISRIC-AfSIS (1 km). It contains all the information DSSAT requires in significant agricultural areas, such as soil bulk density, organic carbon, percentage of clay and silt, soil pH and cation exchange capacity. The layer characteristics include saturated hydraulic conductivity, soil water content at field capacity, wilting point, and saturation.

The weather files were created with historical data from 1990 and predictions for up to 2050 from the SSPs scenarios from The Sixth Phase of CMIP. We used downscaled versions with fine spatial resolution of $0.25^\circ \times 0.25^\circ$ (948 grid cells) of air temperature, precipitation, relative humidity, solar radiation, and wind speed from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) [43]. In this study, we used the following Global Climate Models (GCMs): ACCESS-CM2, ACCESS-ESM1-5, CanESM5, CMCC-ESM2, EC-Earth3, EC-Earth3-Veg-LR, GFDL-ESM4, INM-CM4-8, INM-CM5-0, and MPI-ESM1-2-LR.

2.2. Simulation scenarios

We analyzed each canola hybrid response under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 [44,45] to investigate canola's productivity under a changing climate in combination with scenarios of changing planting dates and nitrogen concentration. We simulated 24 planting dates for spring canola at three-day intervals following Wu et al. [23] findings to avoid temperature and water stresses. Typical planting dates in the Canadian Prairie Region start in late April, when 0 °C no longer occurs [23] and finish in mid-June. Insurance companies stipulated June 20 as the last insurable planting date [46]. Considering extreme early and late dates to evaluate planting date shifting, we simulated sowing on April 1, April 5, April 9, April 13, April 17, April 21, April 25, April 29, May 3, May 7, May 11, May 15, May 19, May 23, May 27, May 31, June 4, June 8, June 12, June 16, June 20, June 24, June 28, and July 2. We also identified the best nitrogen concentration for canola production in the Canadian Prairie Region by simulating five treatments, based on Wen et al. [47] findings, encouraging a split application of Nitrogen (divided into pre-plant and top-dressing) to promote better nitrogen use efficiency and less loss of nitrogen to leaching or volatization. We applied 100, 125, 150, 175, and 200 kg N ha^{-1}, 33 % at seeding and 67 % 30 days after planting since nitrogen accumulation is higher during vegetative stages [48] and as a mitigation strategy to reduce the emission of greenhouse gases from fertilization [47].

The SSP scenarios represent the most to the least optimistic future narratives. The SSP1 scenario considers that the world grows sustainably within environmental boundaries. A vast change in social, economic, and technological trends is not expected in the SSP2 since it includes uneven income and development across the globe. The SSP3 scenario shows high challenges to adaptation and mitigation and is policy-oriented. It will develop towards security matters, allowing countries to reach energy and food security goals with low population expansion. The fifth SSP narrates fast technological and human capital progress, reflecting heavy fossil fuel resource exploitation [45] for a detailed description). The variation of precipitation and temperature for all the simulated scenarios is shown in Fig. 2. Precipitation is not expected to be highly affected by the climate scenarios until 2050 (Fig. 2). All simulated productions were exclusively rainfed in this study, which allows us to account for water deficit and the impact of temperature on water availability, besides analyzing canola's development without irrigation. Expected precipitation changes by 2050 reach 1 ± 4 % across all SSPs, with no statistically significant differences between scenarios [44]. Temperatures are expected to rise by 2050, especially under SSP5-8.5. Projected temperature increases by 2050 relative to the historical baseline (1990–2014) are 1.5 ± 3 °C for SSP1-2.6, 1.9 ± 4 °C for SSP2-4.5, 2.4 ± 4 °C for SSP3-7.0, and 3.0 ± 4 °C for SSP5-8.5. Thus, the warming under SSP5-8.5 is approximately twice as large as that under SSP1-2.6 [44].

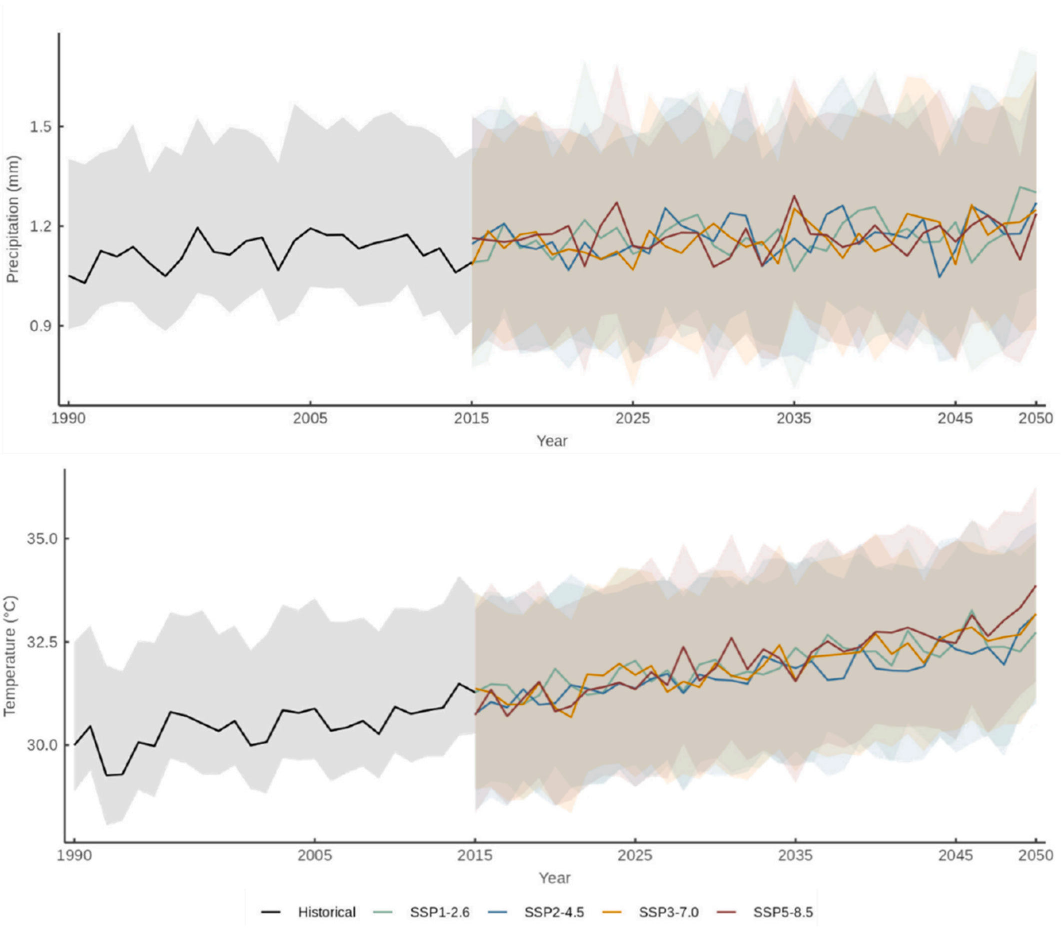

Fig. 2. Mean daily precipitation (mm) and temperature (°C) for historical and SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

3. Results

3.1. DSSAT performance

The most common method to calibrate a crop model is by comparing observed crop characteristic data from farms or field trials with similar management practices of interest to the simulated values. Including detailed data such as the Leaf Area Index, biomass, and yield-to-crop model calibrations may improve yield prediction accuracy [49]. This comparison between observed and simulated data enables the calibration of the crop genetic parameters in the model (Table 1). The parameters obtained during calibration were used to evaluate the model's

Table 1

Parameters used for canola hybrids InVigor®-L233P, InVigor®-L340PC, InVigor®-L343PC, and InVigor®-L350PC for calibration of phenology (P) and growth (G), or not used for calibration, only simulation (N).

Parameter	Definition	Use	L233P	L340PC	L343PC	L350PC
CSDL (hour)	Critical Short-Day Length below which reproductive development progresses with no daylength effect	P	16	16	16.87	16
PPSEN (1/hour)	Slope of the relative response of development to photoperiod with time	N	−0.011	−0.011	−0.011	−0.011
EM-FL (PD[a])	Time between plant emergence and flower appearance	P	28.5	28.7	28.09	33.07
FL-SH (PD)	Time between first flower and first pod	P	11	12.7	13.95	13.29
FL-SD (PD)	Time between first flower and first seed	P	15.5	18.9	17.93	17.65
SD-PM (PD)	Time between first seed and physiological maturity	P	22.5	25.76	27.75	26.24
FL-LF (PD)	Time between first flower and end of leaf expansion	P	2.5	2.09	5.841	4.457
LFMAX (mg CO_2/m^2-s)	Maximum leaf photosynthesis rate at 30 °C, 350vpm CO_2, and high light	N	1.28	1.28	1.28	1.28
SLAVR (cm^2/g)	Specific leaf area of cultivar under standard growth conditions	G	330	330	225.4	214
SIZLF (cm^2)	Maximum size of full leaf	G	100	100	100	100
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	N	1	2	1	1
WTPSD (g)	Maximum weight per seed	N	0.002	0.002	0.002	0.002
SFDUR (PD)	Seed filling duration for pod cohort at standard growth conditions	G	23	20.8	23.7	14.5
SDPDV (number/pod)	Average seed per pod under standard growing conditions	G	22	22	22	22
PODUR (PD)	Time required for cultivar to reach final pod load under optimal condition	G	4	3.2	3.227	3.088
THRSH	The maximum ratio of *seed/(seed + shell)* at maturity	N	95	95	95	95
SDPRO	Fraction protein in seeds	N	0.23	0.23	0.23	0.23
SDLIP	Fraction oil in seeds	N	0.48	0.48	0.48	0.48

[a] PD = Photothermal Days.

performance.

The model's performance showed satisfactory predictions of grain yield for all hybrids during calibration and validation (Fig. 3). The mean difference between observed and simulated yield data during calibration and validation was 1.24 %, 2.6 %, 0.25 %, and 10.2 % for InVigor®-L233P, InVigor®-L340PC, InVigor®-L343PC, and InVigor®-L350PC, respectively. We observed a mean difference of less than 35 kg ha^{-1}, 62 kg ha^{-1}, 8.5 kg ha^{-1}, and 234 kg ha^{-1} of grain yield during validation for InVigor®-L233P, InVigor®-L340PC, and InVigor®-L343PC, and InVigor®-L350PC, respectively. We attribute simulated data variation to the lack of initial boundary data in the soil input, as yield underestimation happens when the soil conditions or the nitrogen application can not be replicated [50]. Nevertheless, yield values across all hybrids demonstrated excellent normalized Root Mean Square Error (nRMSE), Coefficient of Determination (R^2) and Index of Agreement (d), thereby confirming the model's accuracy (Fig. 3).

3.2. Canola hybrids

Focusing on the spatial performance of each hybrid, we demonstrate the best productivity of each hybrid in terms of yield (kg ha^{-1}) within the Canadian Prairie Region on a temporal (annual) average (Fig. 4). InVigor®-L233P was the most productive hybrid when planted early in the season (Fig. 4), especially at SSP2-4.5, with absolute dominance until April 17 (Supplementary Fig. S1). InVigor®-L340PC has appeared as the most productive hybrid in some small spots in Alberta and

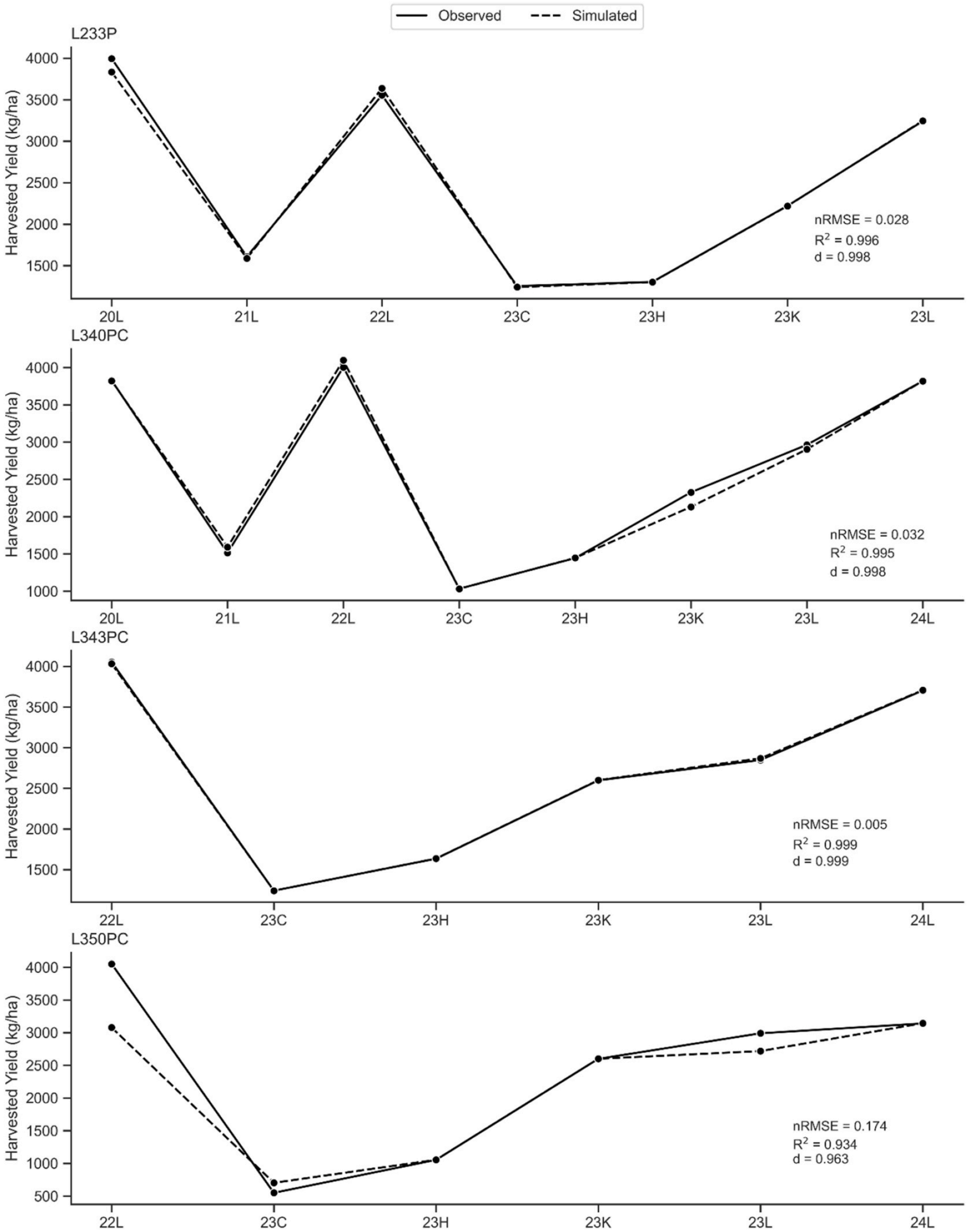

Fig. 3. The observed and simulated values of Yield (kg ha^{-1}) during calibration and validation of DSSAT CSM-CROPGRO-Canola for the canola hybrids InVigor®-L233P, InVigor®-L340PC, InVigor®-L343PC, and InVigor®-L350PC, in Conrad (C), Havre (H), Kalispell (K), and Langdon (L) from 2020 to 2024 (20–24).

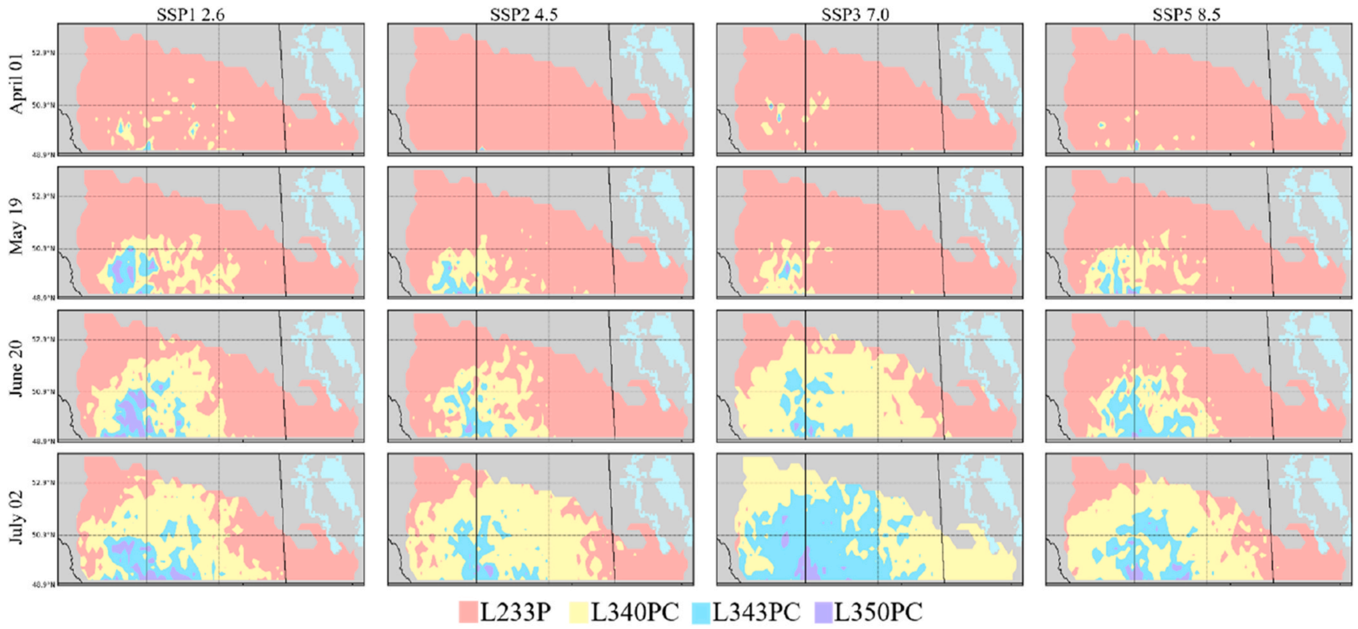

Fig. 4. Map of maximum productivity in terms of yield (kg ha^{-1}) on time (years) average for the canola hybrid InVigor®-L233P, InVigor®-L340PC, InVigor®-L343PC, and InVigor®-L350PC.

Saskatchewan at SSP1-2.6, SSP3-7.0, and SSP5-8.5 since April 1. On later planting dates, it expands its productive area with the greatest yield (kg ha^{-1}) across all scenarios. This expansion happens particularly in the drier areas of Canadian Prairie Region, except on later dates at SSP3-7.0 when it is found in the northwest and southeast regions (Fig. 4). Meanwhile, InVigor®-L343PC offers the best productivity in the drier areas. InVigor®-L350PC is seen as best productive in localized spots since April 1 at SSP3-7.0, April 5 at SSP1-2.6, and April 17 at SSP2-4.5 and SSP5-8.5; however, its domain becomes more expressive in June or July (Supplementary Fig. S1).

Focusing on the best planting date of each hybrid, we show how each hybrid performed across various planting dates under climate change scenarios (Fig. 5). InVigor®-L340PC showed a higher yield (kg ha^{-1}) for all future scenarios and planting dates within the Canadian Prairies, with most values between 2500 and 3000 kg ha^{-1}. InVigor®-L343PC had the second-best yield (kg ha^{-1}) in all future scenarios and planting dates, with most values between 1500 and 1800 kg ha^{-1}. InVigor®-L233P and InVigor®-L350PC showed similar results, with the lowest yield values (kg ha^{-1}), most between 1000 and 1300 kg ha^{-1} (Fig. 5). Each future scenario presented a different planting date resulting in the best yield productivity for canola on the Canadian Prairies. From the four scenarios simulated, SSP3-7.0 was the only one in which maximum

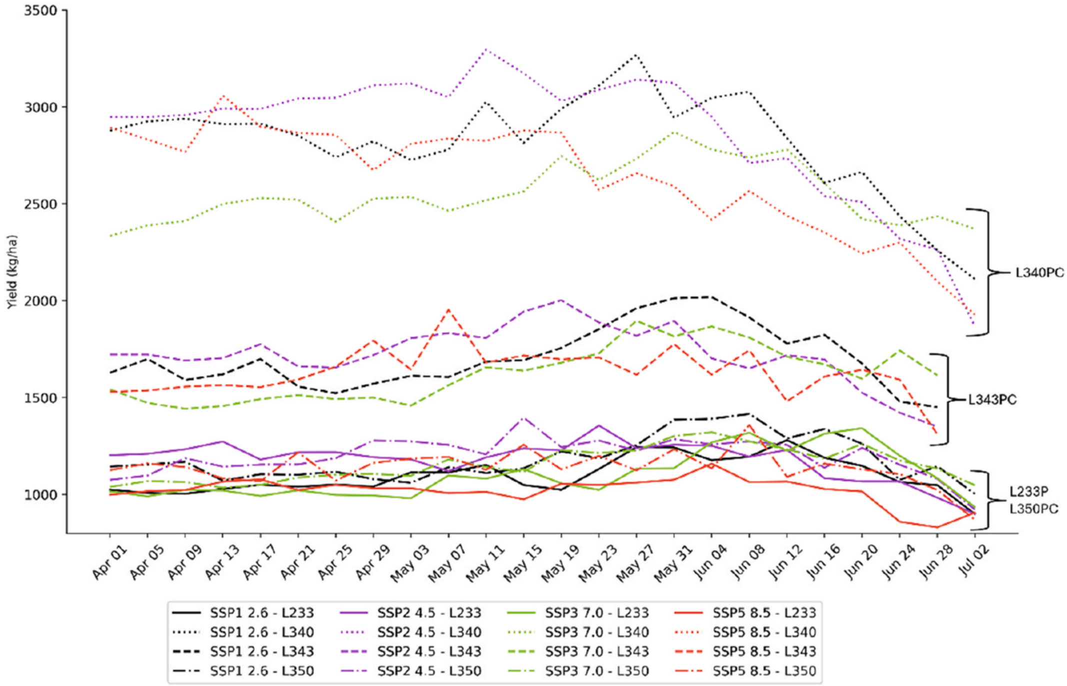

Fig. 5. Maximum hybrid productivity in terms of yield (kg ha^{-1}) for each planting date for the future scenarios with spatial (latitude and longitude) and time (years) average for the canola hybrid InVigor®-L233P, InVigor®-L340PC, InVigor®-L343PC, and InVigor®-L350PC.

canola productivity was lower than 3000 kg ha^{-1}. The highest productivity happened at SSP1-2.6 on May 27, SSP2-4.5 on May 11, SSP3-7.0 on May 27, and SSP5-8.5 on April 13 (Fig. 5).

Integrating the spatial and temporal performance of each hybrid, the early-maturing hybrid InVigor®-L233P has the highest yield values in all growing zones when planted early (Fig. 4) but with lower productivity (Fig. 6). According to BASF® Canada Incorporation 2025 Portfolio description, InVigor®-L233P, InVigor®-L340PC, and InVigor®-L343PC show good development in all growing zones of the Canadian Prairies. InVigor®-L343PC differs from InVigor®-L340PC by being a second-generation clubroot-resistant hybrid. It is recommended for areas with more clubroot disease occurring [51]. However, simulating disease occurrence or pest attacks is out of the scope of this study. InVigor®-L233P is the oldest hybrid in this study, and its productivity is expected to be lower than that of the other hybrids we analyzed. Overall, InVigor®-L340PC was the hybrid with higher productivity, on spatial and temporal average (Fig. 6).

3.3. Nitrogen concentrations

The shifts in the planting date affected the nitrogen uptake and yield within the Canadian Prairie Region (Fig. 7). The highest nitrogen concentration in fertilization showed greater yield-nitrogen uptake during April and May presented a decline, showing the lowest values by June 2. By planting in June and July, the change in canola suffering from cold and frost stress and lower soil moisture is higher. Abiotic conditions dictate how the plant will absorb nutrients and prioritize growth over reproduction [52]. There is a waste of nitrogen when applying higher concentrations during non-ideal environmental conditions, which shows lower concentration fertilization and higher yield-nitrogen uptake

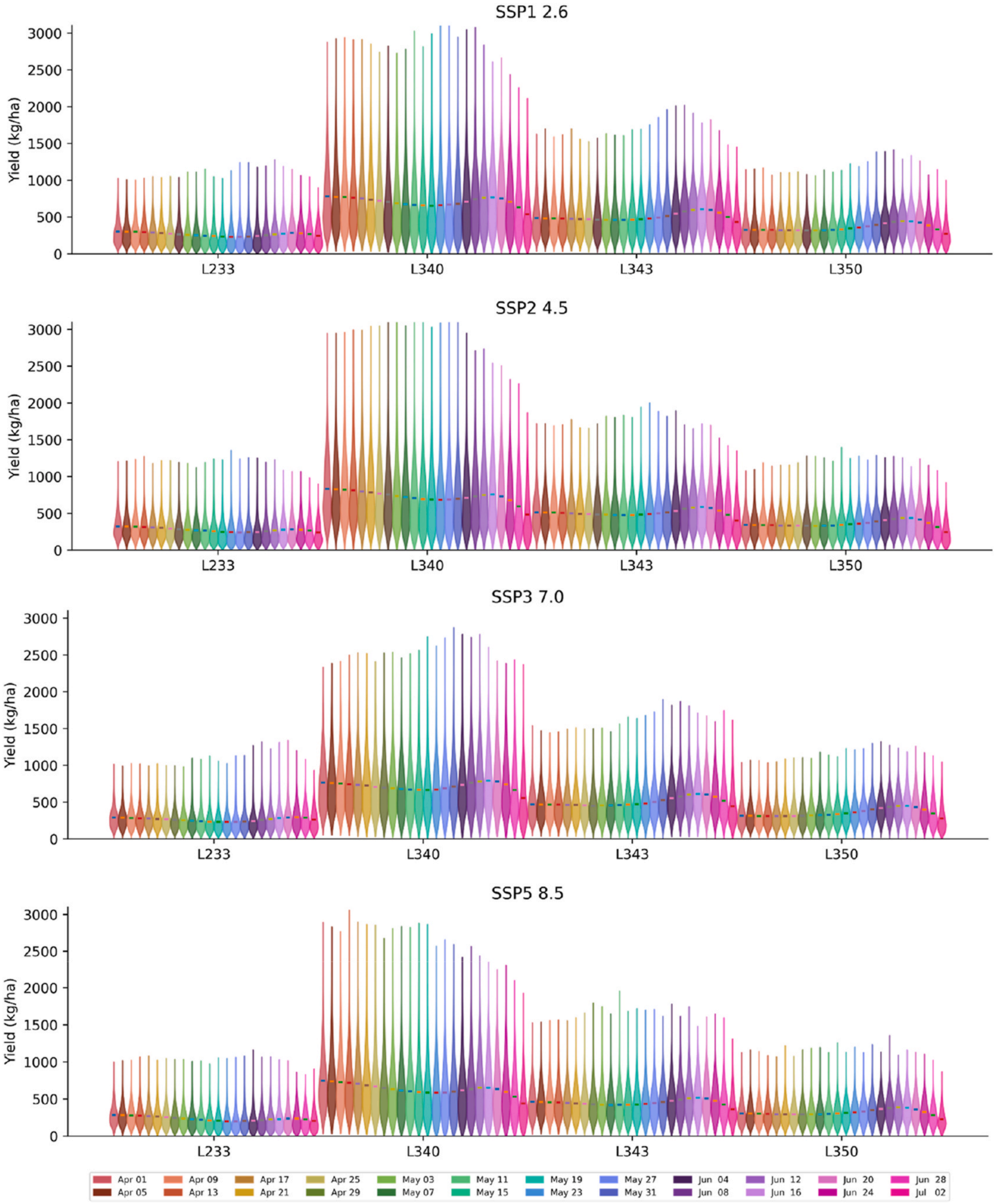

Fig. 6. Mean hybrid productivity in terms of yield (kg ha^{-1}) for each planting date with spatial (latitude and longitude) and temporal (years) average for the canola hybrids InVigor®-L233P, InVigor®-L340PC, InVigor®-L343PC, and InVigor®-L350PC.

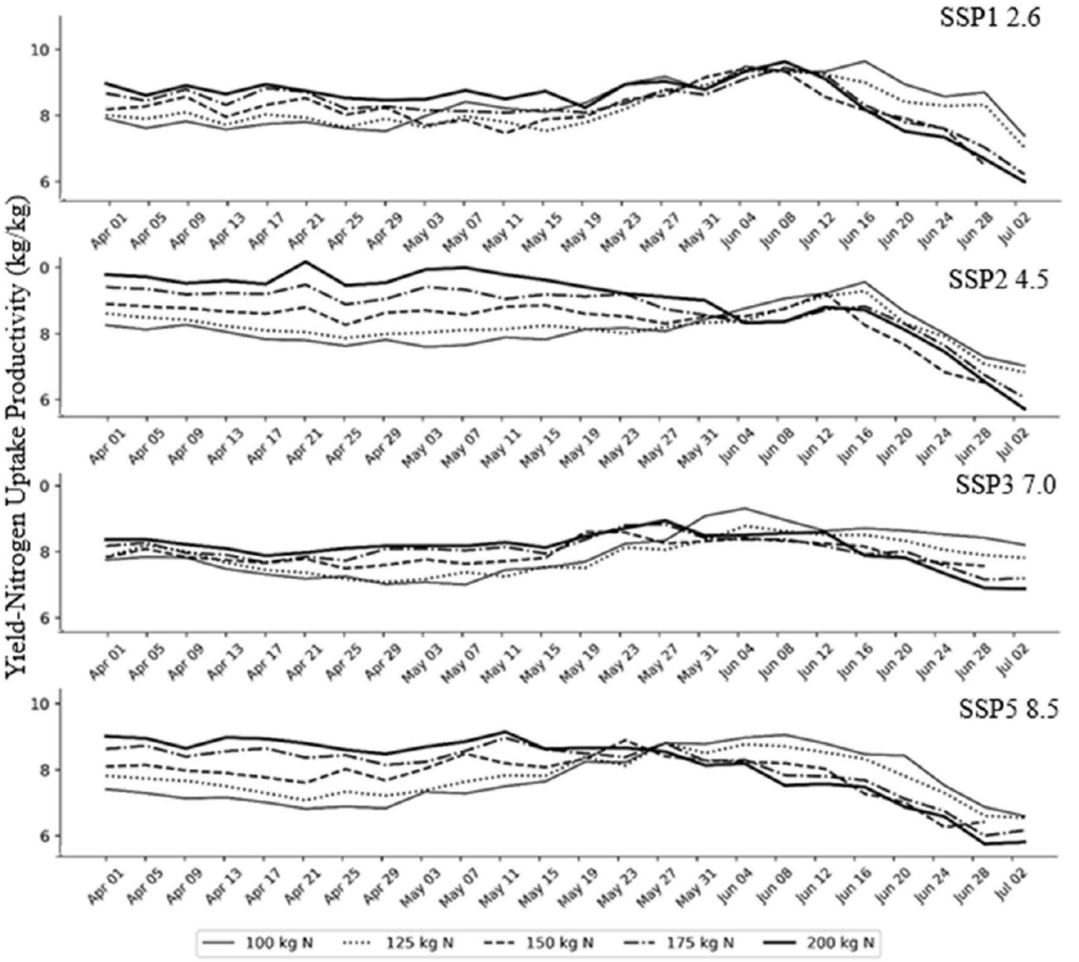

Fig. 7. Maximum Yield-Nitrogen uptake productivity in terms of yield (kg kg^{-1}) for each planting date under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 with spatial (latitude and longitude) and time (years) average for fertilization with the nitrogen concentrations 100, 125, 150, 175, and 200 kg N ha^{-1}.

productivity. This decrease in nitrogen uptake happens at earlier planting dates at SSP5-8.5 on May 27 and later at SSP1-2.6 on June 12 (Fig. 7).

On spatial and temporal averages, the nitrogen concentration in the fertilization treatments positively affected canola yield as canola increased productivity with the increase in N concentration (Fig. 8). Overall, all the hybrids benefited from a higher N concentration application. SSP1-2.6 presented similar yield values in April and May within each treatment, with the highest productivity in June for the treatments applying 100 and 125 kg N ha^{-1} and in May for applications of 150, 175, and 200 kg N ha^{-1}. SSP2-4.5 showed similar productivity for planting dates during April and May and a decrease in yield of approximately 10–20 % in June and up to approximately 30 % on July 2. SSP3-7.0 shows a clear ascent for the treatments with 100 and 125 kg N ha^{-1}, a sinuous curve when applied 150 kg N ha^{-1}, and a descending curve for planting dates in June and July for applications with 175 and 200 kg N ha^{-1}. SSP5-8.5 resulted in two peaks of yield in mid-April and mid-May for all treatments, with the highest values found on April 13 (Fig. 8).

In contrast, Fig. 9 shows the best spatial productivity in yield (kg ha^{-1}) according to the nitrogen concentration applied in fertilization within the Canadian Prairie Region on temporal average (years). Application with 200 kg N ha^{-1} was dominantly more productive before April 25, when 175 kg N ha^{-1} became more expressive in all future scenarios, especially at SSP3-7.0 (Supplementary Fig. S2). Lower concentrations increased productivity during May in Alberta and Saskatchewan, mainly at SSP1-2.6 and SSP5-8.5 (Fig. 9). N concentrations of 125 and 150 kg N ha^{-1} derived higher productivity results in the drier area of the Canadian Prairie Region at later planting dates, primarily at SSP2-4.5 and SSP3-7.0, respectively (Fig. 9). As for Manitoba, 100 and 125 kg N ha^{-1} were not expressive in showing the highest yield in all future scenarios and planting dates. Overall, Manitoba showed relatively similar behaviour regarding nitrogen fertilization and canola yield, with 150 kg N ha^{-1} showing highest yield in June at SSP5-8.5, the biggest highlight (Supplementary Fig. S2).

4. Discussion

We found similarities in hybrid productivity on spatial and temporal averages but expressive differences in the spatial analysis (Fig. 4). Hybrid performances are mostly linked to the planting dates, weather and soil conditions, the period to reach maturity, and the zones where they are planted. The Hardiness Zone Map relates plant physiology to climate and estimates the impacts over the planting season of various plant species [53]. Planting spring canola is recommended in all zones of the Canadian Prairie Region, most occurring in the northern and central growing areas [54]. The Annual Performance Variety Trial Program executed canola regional trials, which reported data from small and field-scale experiments across the Prairies [55]. For 2022, InVigor®-L340PC yield had a similar performance to InVigor®-L343PC for most of the sites in Alberta. InVigor®-L340PC showed higher results for mid-growing zone sites and worse for long-growing zone sites in Alberta. In Saskatchewan, InVigor®-L340PC showed higher yields than InVigor®-L343PC in the 2024 Trial Summary as Agronomic Excellence trials from BASF® in 88 % of the sites [56]. InVigor®-L340PC also ranked top

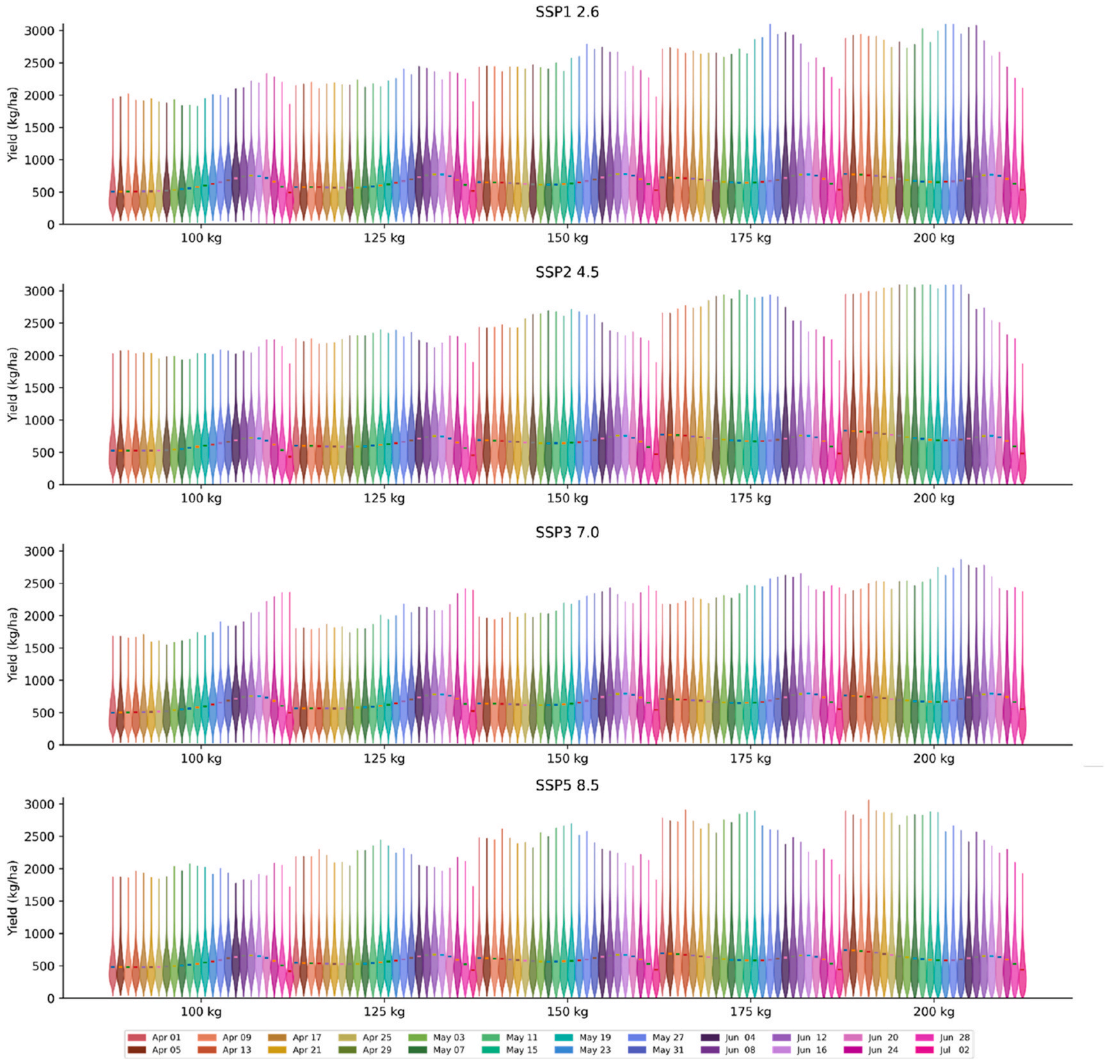

Fig. 8. Mean productivity in terms of yield (kg ha^{-1}) for each planting date with spatial (latitude and longitude) and time (years) average for fertilization with the nitrogen concentrations 100, 125, 150, 175, and 200 kg N ha^{-1}.

for yield in mid and long-growing zones in the 2024 Demonstration Strip Trials from BASF® in Saskatchewan [57]. InVigor®-L350PC is the most recently released hybrid included in this study. It was expected to have a higher yield potential than the other hybrids. BASF Corporation (2025b) states InVigor®-L350PC's potential yield of 114.3 % of InVigor®-L233P. However, yield results for InVigor®-L350PC and InVigor®-L233P were very similar. We attribute these results of our simulations being only rainfed, reducing InVigor®-L350PC's potential, mainly because this hybrid thrives in irrigated areas [58].

It is possible to improve canola's resilience to abiotic factors through breeding techniques, but on-farm management practices and adaptation strategies must be considered [59]. In a previous study, we identified the canola farmers' adaptation strategies are deemed viable when producing on the Canadian Prairies, where all survey participants considered irrigation a non-viable option [60]. According to Wu et al. [61] findings in Saskatchewan, the authors considered the SSP1-2.6 and SSP2-4.5 scenarios (when mild temperature rises and rainfall decreases, and higher temperature and rainfall rise, respectively) easily adaptable to irrigation expansion strategies. Differing from the SSP3-7.0 scenario (when temperature rises and rainfall decreases), they considered adapting to the same strategy more challenging. This weather variability (Fig. 2) also creates uncertainty in farmers' decision-making over implementing adaptation strategies, primarily due to financial constraints [60].

Considering our map (Fig. 4), we observe that InVigor®-233P has the highest yield values when compared to all the other cultivars in early planting dates (April/May). On later dates, we observe that InVigor®-340PC and InVigor®-343PC showed higher yield than the other cultivars, with more variability in the drier areas. This change in hybrid fit happens because the hybrid with the best fit for rainfed production in the Canadian Prairie Region depends on the climatic conditions besides the planting date, which will affect canola's roots, water and nutrient uptake [52]. Although water availability from precipitation is a crucial environmental problem related to weather that canola production faces, extreme temperatures may counterbalance a scenario with appropriate water availability [62]. Canola is intensely sensitive to temperature [63]. For canola development, the base temperature is 5 °C, the optimum temperature is 26 °C, and the maximum temperature is 40 °C [64]. This study's maximum value for minimum and maximum temperature during the growing season was approximately 47 °C and 63 °C, respectively. This warming enables longer growing seasons and better production conditions in the Northern regions, where it is typically cooler [65]. However, a change in temperature exceeding canola's resistance range alters the plant's physiology, causing it to stop developing to protect itself, as extreme temperatures are lethal [66,67]. In 2021, a heatwave occurred during vital stages of plant development, generating massive yield losses of approximately 30 % for diverse crops in British Columbia and Alberta [10]. As for the minimum value for

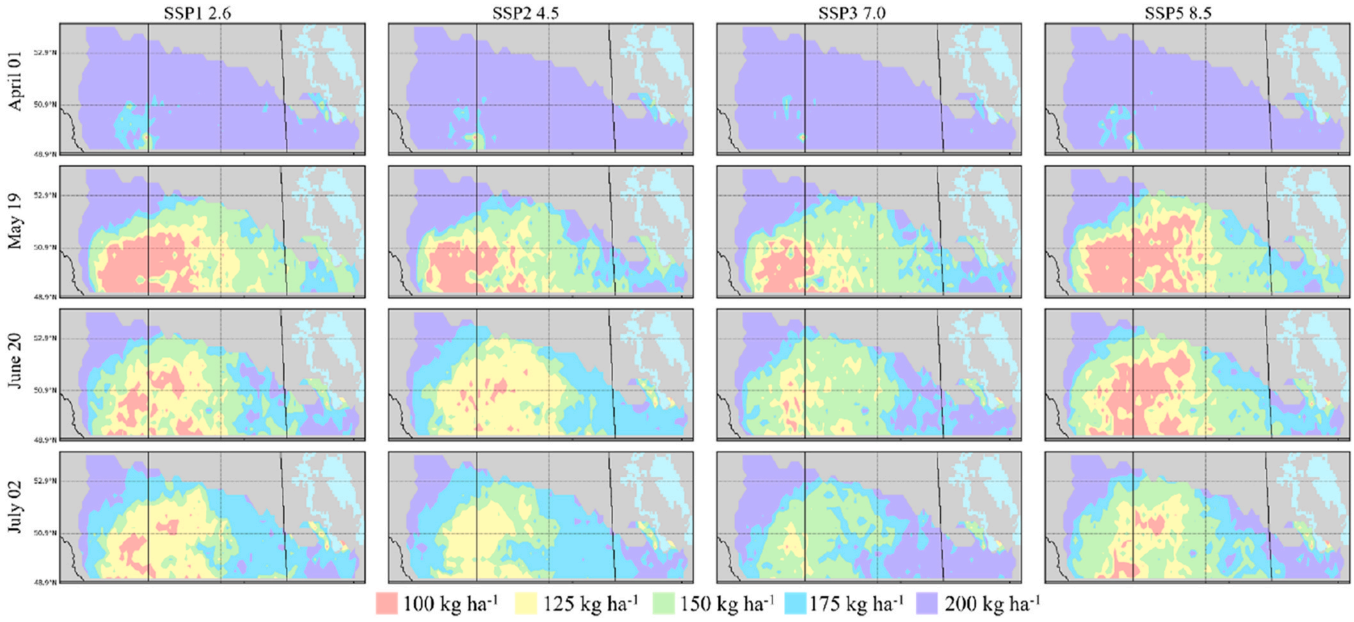

Fig. 9. Map of the maximum productivity in terms of yield (kg ha^{-1}) for fertilization with the nitrogen concentrations 100, 125, 150, 175, and 200 kg N ha^{-1} on time (years) average.

minimum temperature during the growing season, we found approximately $-7°C$ in this study.

Canola planted late may suffer from the high temperatures during Summer during its vegetative development, resulting in smaller plants [63]. Canola may also reach the flowering and grain-filling stages during fall, when the minimum temperatures are below the base for good development and low precipitation. Mild and extreme frost events may occur in the Spring and Fall (Fig. 2). In the early stages of canola development, frost stress may prevent or delay seed germination. It is lethal to seedlings and non-acclimated plants at flowering and grain-filling stages. It damages silique embryos and ovules, causes abortions and infertility, and impairs grain yield (Kovaleski et al., 2020; Wrucke et al., 2019). Hence, shifting planting dates according to weather forecasts is essential to prevent damage to canola.

By analyzing the 24 planting dates, we found that the current canola hybrid cultivars explored are expected to grow and achieve higher productivity when planted around April 13 under a very hot scenario (SSP5-8.5), May 11 under a hot scenario (SSP2-4.5), and May 27 under a scenario with mild temperatures (SSP1-2.6 and SSP3-7.0). Planting date changes are recommended when severe weather conditions and variability occur [63] and are remarkably accepted as an adaptation strategy by canola farmers in the Prairies [60]. It is well-known that moving the planting date influences canola establishment and yield potential [59]. The shift in the optimal planting date through the scenarios is due to the projected weather [68]. As aforementioned, a three-to-six-day change is expected when a rise of 1 $°C$ occurs [23]. SSP5-8.5's global warming projections are the highest of the simulated scenarios [45]. According to our projections, the higher the temperatures during spring, the earlier producers can plant. However, planting seeds resistant to high temperatures is crucial to endure extremely high temperatures in the Summer. Especially under very hot days, when the accumulation of growing degree days is higher and results in faster maturity rate [69]. Further investigation into the specific and joint effects of climatic variables on planting date shifts is needed to better understand their influence on future spring canola development and yield outcomes. Moreover, adjusting planting dates in conjunction with the selection of climate-adapted hybrids can enhance water use efficiency and increase the harvest index [70]. The hybrids evaluated in this study were specifically developed to perform under current climatic conditions, which is reflected in our results, as the highest simulated yield was observed under the SSP2-4.5 scenario. Besides finding the optimal planting window, good management practices are crucial to promoting sustainable production under climate variability. Here, we found that, overall, applying the highest N concentration in the fertilization resulted in greater yield. However, this changes when fertilization effects are analyzed spatially and over the planting dates (Fig. 9). A declining curve is noticeable in yield-nitrogen uptake productivity for canola planted from mid-June on in all scenarios (Fig. 7). In contrast, there was no oversupply of N at any rate, as our results indicate the decrease in yield-nitrogen uptake productivity is due to the planting date and abiotic effects. Extremely high temperatures found in the Summer, causing daily stress and thermal accumulation during the flowering stage, preventing canola from reaching its yield potential related to N fertilization [47], which is noticeable mainly in drier places on the Prairies (Fig. 9). Canola depends on nitrogen availability to establish, develop, and fill the grains, and planning fertilization is another adaptation strategy widely accepted by canola producers in the Prairies [60]. High-yielding canola hybrids demand more nitrogen uptake and allocation to produce than parental genotypes [71]. We observed that the hybrid cultivars fertilized with high nitrogen concentrations (200 kg ha^{-1}) usually resulted in higher yields of approximately 2800 ± 300 kg ha^{-1}. Nitrogen fertilization application with high concentration (200 kg ha^{-1}) is expected to be more effective before May 19 under very hot scenarios (SSP5-8.5) and before June 08 under mild temperatures (SSP1-2.6). Because the higher the temperature and the lower water availability during the growing season (especially during the bolting stage), the less uptake there will be from the plant, and the more waste will be lost through leaching or volatilization [47]. Therefore, we recommend the application of low N concentration when planting on or after June 16, June 4, May 31, and May 27 under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively, particularly in the drier areas of the Prairie Region. These findings are consistent with previous studies demonstrating that environmental conditions change canola's response to nitrogen fertilization. Furthermore, their results confirm that canola yield tends to plateau when nitrogen application concentrations range between 100 and 200 kg ha^{-1} [70]. In addition, planning its application according to weather conditions and other management practices, such as shifting planting dates, help avoid ecosystem contaminations by promoting good nitrogen use efficiency [24,47,48].

Since modern hybrids are developed to resist the attack of pests and diseases and are recommended for areas with more occurrence, especially clubroot disease in the Canadian Prairies [51], we suggest future studies simulating disease occurrence and pest attacks. In addition, assessment of future canola productivity will benefit from the evaluation of specific and joint effects of climatic variables. Moreover, a partnership between breeder institutions, hybrid developers, and crop modeller researchers would benefit the community with new and updated input data that is usually kept confidential in the private industry for adding new hybrids and calibrating the models accordingly, which may limit DSSAT calibration for regional- or hybrid-specific simulations.

5. Summary and conclusion

Canola's performance is susceptible to temperature and precipitation, especially in rainfed production. Spring canola in the Canadian Prairie Region is often subjected to frost events at the beginning or end of the growing season, as well as extended dry periods, mainly in the central southern part of the region. Understanding how current hybrids would grow and reproduce in the future may enlighten farmers and breeders on the needs for the future. We used DSSAT to simulate four canola hybrids, 24 planting dates, five nitrogen concentrations, and four future climate scenarios, with a spatial resolution of $0.25^\circ \times 0.25^\circ$ in the Canadian Prairie Region to analyze the impacts of high and low temperatures and water deficit damages on the spring canola production.

The greatest canola productivity occurred with the early planting date (April) for SSP5-8.5 and mid-planting dates (May) for the other scenarios. Late planting dates resulted in lower productivity, with the plants suffering from heat, frost, and dry periods. Drier areas of the Prairie Region showed less nitrogen uptake from the plant, which resulted in less yield. Better weather conditions prompted higher nitrogen uptake, impacting canola's development and productivity. Our results show that higher N concentrations (up to 200 kg N ha^{-1}) could lead to higher yields in ideal environmental conditions. However, nitrogen fertilization must be carefully planned to avoid environmental contamination and ensure good efficiency of nitrogen use. Hence, appropriately planning fertilization considering location, climate and soil conditions is essential to prevent the side effects of nitrogen in the environment. Overall, canola developed well in final yield in all early and mid-planting dates, reaching low productivity when planted late in July. There was a higher variability among the hybrids that best fit in the drier area of the Canadian Prairie Region (central southern), with fewer changes in the Northwest area of the Prairie Region in Alberta and the whole Region in Manitoba.

We expect this study to help farmers' and shareholders' decision-making over the purchase and sowing of the appropriate canola seed to their farm location and management conditions, besides being able to reduce the concentration of nitrogen fertilization when environmental conditions are not ideal for nitrogen uptake by the plant. Also, it serves as a discussion point for insurance companies and insurable planting deadlines. Although we cannot dictate how the weather will be, we can use the SSP scenarios to find possible outcomes and prepare for adaptation and mitigation as soon as possible.

CRediT authorship contribution statement

Yohanne Larissa Gavasso-Rita: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Hebatallah Abdelmoaty:** Writing – review & editing. **Yanping Li:** Writing – review & editing, Funding acquisition. **Simon Michael Papalexiou:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2025.102574.

Data availability

Data will be made available on request.

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