Science of the Total Environment 892 (2023) 164502

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Phenological phase affects carrot seed production sensitivity to climate change – A panel data analysis

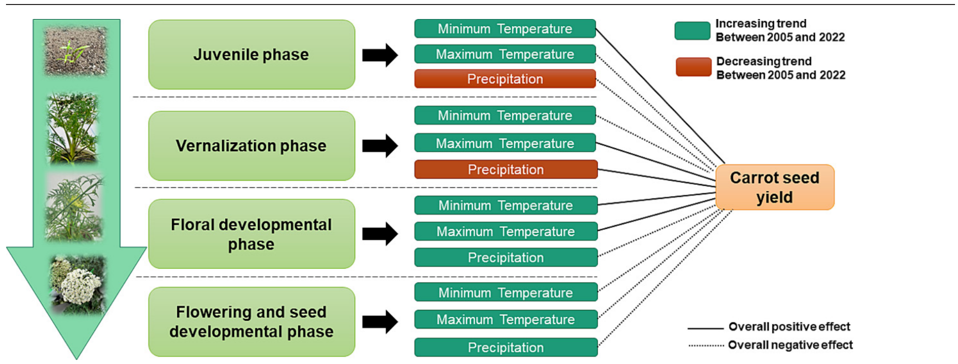
Asharp Godwin [a,b,*], Craig McGill [a], Andrew Ward [c], Svetla Sofkova-Bobcheva [a], Simone Pieralli [a,d]

[a] School of Agriculture and Environment, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand
[b] Department of Agronomy, Faculty of Agriculture, University of Jaffna, Ariviyal Nagar, Kilinochchi, Sri Lanka
[c] AsureQuality Limited, Batchelar Agriculture Centre, Tennent Drive, PO Box 609, Palmerston North 4440, New Zealand
[d] European Commission Joint Research Centre, 41092 Seville, Spain

HIGHLIGHTS

- First report on modeling the impact of climate change on carrot seed production.
- Rainfall and temperature at distinct phenology of carrot seed crop was modeled.
- Temperature in carrot seed producing regions has been rising considerably since 2005.
- High rainfall at the reproductive phase was detrimental to carrot seed yield.
- Carrot seed production in New Zealand will be impacted by subsequent climate change.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Elena Paoletti

Keywords:
Carrot seed crop
Marginal effect
New Zealand
Phenology
Regression
Seed yield

ABSTRACT

New Zealand is a major producer of carrot seeds globally. Carrots are an important nutritional crop for human consumption. Since the growth and development of carrot seed crops mainly depend on climatic factors, seed yield is extremely susceptible to climate change. This modeling study was undertaken using a panel data approach to determine the impact of the atmospheric conditions (proxied by maximum and minimum temperature) and precipitation during the critical growth stages for seed production in carrot, viz., juvenile phase, vernalization phase, floral development phase, and flowering and seed development phase on carrot seed yield. The panel dataset was created using cross-sections from 28 locations within the Canterbury and Hawke's Bay regions of New Zealand that cultivate carrot seed crops and time series from 2005 to 2022. Pre-diagnostic tests were performed to test the model assumptions, and a fixed effect model was selected subsequently. There was significant ($p < 0.01$) variability in temperature and rainfall throughout different growing phases, except for precipitation at the vernalization phase. The highest rate of changes in maximum temperature, minimum temperature, and precipitation were recorded during the vernalization phase (+0.254 °C per year), floral development phase (+0.18 °C per year), and juvenile phase (−6.508 mm per year), respectively. Based on marginal effect analysis, the highest significant influence of minimum (187.724 kg/ha of seed yield decrease for each 1 °C increment) and maximum temperature (1 °C rise increases seed yield by 132.728 kg/ha), and precipitation (1 mm increment of rainfall decreases the seed yield by 1.745 kg/ha) on carrot seed yield were reported at vernalization, and flowering and seed development, respectively. The minimum and maximum temperatures have a higher marginal effect on carrot seed production. Analysis of the panel data demonstrates that the production of carrot seeds will be vulnerable to climatic change.

* Corresponding author at: School of Agriculture and Environment, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand.
E-mail address: a.godwin@massey.ac.nz (A. Godwin).

http://dx.doi.org/10.1016/j.scitotenv.2023.164502
Received 5 April 2023; Received in revised form 24 May 2023; Accepted 25 May 2023
Available online 1 June 2023

1. Introduction

Long-term variation in the behavior of meteorological indices is known as climate change (Aliev et al., 2023; Jakob and Walland, 2016). The rising vulnerability of many nations to natural catastrophes due to climate change makes climate change a global issue (Tan et al., 2021). Signals of ongoing climate change on a global scale are both understandable and unavoidable (Carroll and Aarrevaara, 2021; Chan et al., 2021). Changes in the pattern of atmospheric temperature and precipitation have been reported across the world (Guo et al., 2021; Todaro et al., 2022). Food security may also be adversely affected by climate change (Sinnarong et al., 2019). Agriculture depends on climatic conditions, particularly temperature and rainfall, hence, crop productivity is extremely sensitive to climate change (Zhang et al., 2022). Many researchers have modeled the impact of changing climatic factors on crop productivity and have found that rising atmospheric temperatures and variations in precipitation affect both the quality and quantity of agricultural commodities (Abbas, 2022; Chaudhry and Sidhu, 2022; Warsame et al., 2021; Yerlikaya et al., 2020). A key requirement for food and nutritional security is the availability of high-quality seed in sufficient quantities when needed for crop production (Madin et al., 2022). Hence, the impact of climate change on seed production also needs to be determined.

Geographical and soil conditions allow New Zealand to produce high-quality seeds for >50 different crops (Melhuish, 2008; Ministry of Foreign Affairs, 2017), including high-quality carrot seed (*Daucus carota* L. subsp. *sativus)*, to meet international demand (Aitken and Warrington, 2018; Broussard et al., 2017; Hampton et al., 2012; Selvakumar and Kalia, 2022). Around 50 % of the world's carrot seed is produced in New Zealand (Preece, 2023). Due to their biennial behavior, carrots, a crop in the Apiaceae family, take about 13 months to complete the process of producing seeds (Junaid et al., 2023; Merfield et al., 2008). Carrot is grown in New Zealand primarily, in Canterbury but also in Hawke's Bay, and is sown in New Zealand during summer for seed production. The cultivation season begins in February and finishes in March of the following year. Cool winter temperatures are an essential requirement to induce the flowering of carrots, which is easily achieved in New Zealand during June and July (Merfield et al., 2010). After the completion of the vernalization phase, the carrot starts to initiate floral development (Linke et al., 2019). In New Zealand, reproductive growth, including the development of floral organs and flowering, occurs generally from September to late February. Harvesting of carrot seeds is typically completed in March (Davidson et al., 2010; Howlett, 2012; Howlett and Gee, 2019). According to the variety, climate, management practices, and geographical factors, the cropping calendar of carrot seed crops can marginally differ from region to region. Carrot, which is high in vitamin A, is regarded as an important vegetable for human consumption (Maurya et al., 2022). Due to its nutritive value and the increase in the global population, the consumption of carrots has climbed in recent years (Duran and Ipek, 2022). As a result, demand for carrots has increased around the world, creating a huge market for carrot growers and a consequent need for increased carrot seed supply (FAOSTAT, 2023; Galletti et al., 2020; Simon, 2019).

Changes in temperature and precipitation can have an impact on each growing phase of a carrot seed crop (Broussard et al., 2017; Deleuran and Boelt, 2009). The influence of vernalization temperature on the rate of carrot flowering was demonstrated by Atherton et al. (1990). Likewise, Quagliotti (1967) and Hiller and Kelly (1979) indicated the negative effect of temperature on floral stalk development of carrots. Furthermore, Broussard et al. (2017) and Chira et al. (2008) studied the behavior of the carrot flower and floral parts in response to climate change and found a reduction in the performance of floral organs with increasing temperature. In addition, Broussard et al. (2017) suggested components in carrot flowers that attract pollinators can be affected by higher temperatures, with a consequent effect on the foraging behavior of pollinators. The impact of warm temperatures on the quality of carrot seeds was researched by Elballa and Cantliffe (1996), who found that the higher temperature during pollination, fertilization, and initial phases of seed development can significantly decrease the seed yield and seed quality of carrots. Germination and seedling growth of carrots can be inhibited by dry conditions caused by a lack of soil moisture and fewer extreme rainfall events (Andriamparany et al., 2020; Schmidhalter and Oertli, 1991). Soil moisture deficit is one of the important limiting factors in the production of quality taproots. A warmer, drier environment in carrot seed production areas will likely impact seed production (Jagosz et al., 2019; Lada et al., 2005; Léllis et al., 2017; Reid and Gillespie, 2017).

Consistent with an approximately linear trend during the 1970s, the world warmed by 0.25 °C from 2011 to 2021 (Robinson et al., 2021). New Zealand's average temperature has climbed by 1.13 ± 0.27 °C from 1909 to 2019. Furthermore, there has been an increase in the minimum and maximum temperatures during the winter compared with the past (Ministry for the Environment and Stats NZ, 2020). In New Zealand, the average atmospheric temperature is projected to increase by 0.8 °C in 2040, by 1.4 °C in 2090, and by 1.6 °C in 2110, compared to 1986–2005 under a mid-range estimation (Ministry for the Environment, 2018). In regard to precipitation, the North Island of New Zealand is likely to receive less precipitation compared with South Island (Climate Change Adaptation Technical Working Group, 2017). The southwestern and northeastern regions of the South Island are predicted to become wetter and drier, respectively (Caloiero, 2020; Macinnis-Ng et al., 2021). Furthermore, as a consequence, drought severity and flooding will be expected to intensify in New Zealand (Booth et al., 2020). These fluctuations in climatic variables could significantly affect New Zealand's agriculture sector (Ausseil et al., 2021; Hopkins et al., 2015). Most extreme events expected to occur in New Zealand are related to changes in temperature and precipitation (Climate Change Adaptation Technical Working Group, 2017). Furthermore, most empirical papers estimating the empirical impacts of climate change on agricultural production employ measures of precipitation and temperature. The identification for the panel data approach comes from weather variation that is, in principle, random. Moreover, temperature and precipitation are potentially correlated and thus need to be included to avoid omitted variable bias (Dell et al., 2014). Consequently, this modeling study focussed on temperature and precipitation as variables.

Modeling approaches have been widely used as a tool to assess the impact of climate change on crop yield (Hasan and Kumar, 2021; Schmidt and Zinkernagel, 2017). These can be classified as process-based models and statistical models (Madhukar et al., 2021). Process-based models predict crop yield by simulating the physiological functions of a plant according to climatic factors, soil factors, management practices, and endogenous characteristics of plants (Chisanga et al., 2020; Crous-Duran et al., 2019; Stratonovitch et al., 2012). The inclusion of crop physiological mechanisms to determine the impact of weather on crop yield is an advantageous feature of process-based modeling. Though, utilizing process models for the predictions of an untested site (actual on-farm conditions) could cause unknown errors. This is due to using particular site-specific experimental data for the validation of the process-based models. Furthermore, factors such as the amount of fertilizer application, pest and disease incidences, and weed-control methods which are dependent on the behavior of farmers cannot be accounted for in the process-based models (Roberts et al., 2017). The inaccessibility of reliable and complete historical data is also one of the constraints of using process-based modeling for climate change projections (Kephe et al., 2021). In contrast to the process-based model, the statistical model requires only historical weather data and productivity data for particular crops for climate-crop modeling (Sinnarong et al., 2019). The statistical modeling approaches can be mainly classified as time series method, cross-section method and panel method (Lobell and Burke, 2010; Meerburg et al., 2009). The main strength of the panel data approach is the incorporation of time series dimension and cross-sectional dimension, which yields more precise model estimations than the other two methods ultimately (Hsiao, 2011). Furthermore, the panel data approach has the ability to control the unmeasured individual heterogeneity in the model. The presence of individual heterogeneity could bias the model parameters (Lockwood and McCaffrey, 2007).

Despite the production of carrot seeds in New Zealand being vital to the availability of high-quality carrot seeds when needed for production of a carrot food crop, this is the first study conducted to analyse the effects of temperature and precipitation on carrot seed production using a panel data approach. There is a major research void in understanding how New Zealand's carrot seed yields will be impacted by climate change and how these can therefore be mitigated. The scientific aims of this panel data study are to identify the pattern of changes in maximum and minimum temperature, and precipitation at different phenological stages of carrots, and to determine the impact of climate change from 2005 to 2022 on carrot seed yield in New Zealand. Furthermore, the research hypothesizes that maximum and minimum temperature, and precipitation are significantly affecting carrot seed yield during juvenile, vernalization, floral development, and flowering and seed development phases. This study provides baseline information to enable the development of mitigation strategies both in New Zealand and other carrot seed producing areas of the world.

2. Material and methods

2.1. Study area and data acquisition

An unbalanced panel dataset was formed comprising 18 years from 2005 to 2022 and 28 regions (103 observations) of New Zealand. Regions from Canterbury (representing the South Island) and Hawke's Bay (representing the North Island) were included. The chosen regions represent an already well-established carrot-seed production region (Canterbury) and a developing carrot-seed production region (Hawke's Bay). To understand the effect of changes in temperature and precipitation during different phenological stages of carrots on seed yield, the study covered phenological stage-specific climatic variables. The juvenile phase, vernalization phase, floral development phase and flowering and seed development phase are also practically matched with autumn, winter, spring, and summer seasons, respectively. The region-wise monthly maximum temperature (T_{max}), minimum temperature (T_{min}) and precipitation were obtained from the national climate database, New Zealand (https://cliflo.niwa.co.nz/). To represent the climatic factors in the different phenological stages of carrots, the temperature and precipitation data were averaged and summed based on months relevant to each phenological stage. Similar studies by Liu et al. (2018) and Li et al. (2021) on changing climate and crop yields were used as a guide for the computation of these averages and summing over the phenological stages. Seed yield data from carrot seed-producing regions from 2005 to 2022 were obtained from South Pacific Seeds Ltd. South Pacific Seeds Ltd. is one of the leading vegetable seed-producing companies in New Zealand. The precipitation, T_{max} and T_{min} were the explanatory variables, and the yield of carrot seeds was the response variable in the model. A description of the included explanatory variables in the panel data model is in Table 1.

2.2. Model specification and estimation

According to previous studies (Busu, 2019; Pipitpukdee et al., 2020), this empirical study is suitable for regression modeling at the carrot-growing regional level to examine the relationship between climatic variables and seed yield of carrots in New Zealand. We specify statistical yield as a function of climatic variables as shown in Eq. (1):

$$\begin{aligned} Y_{it} = {} & \beta_0 + \beta_1 JTmin_{it} + \beta_2 JTmin_{it}^2 + \beta_3 JTmax_{it} + \beta_4 JTmax_{it}^2 + \beta_5 Jpre_{it} \\ & + \beta_6 Jpre_{it}^2 + \beta_7 VTmin_{it} + \beta_8 VTmin_{it}^2 + \beta_9 VTmax_{it} + \beta_{10} VTmax_{it}^2 \\ & + \beta_{11} Vpre_{it} + \beta_{12} Vpre_{it}^2 + \beta_{13} FDTmin_{it} + \beta_{14} FDTmin_{it}^2 \\ & + \beta_{15} FDTmax_{it} + \beta_{16} FDTmax_{it}^2 + \beta_{17} FDpre_{it} + \beta_{18} FDpre_{it}^2 \\ & + \beta_{19} FLTmin_{it} + \beta_{20} FLTmin_{it}^2 + \beta_{21} FLTmax_{it} + \beta_{22} FLTmax_{it}^2 \\ & + \beta_{23} FLpre_{it} + \beta_{24} FLpre_{it}^2 + \alpha_i + \varepsilon_{it} \end{aligned} \quad (1)$$

The i and t in Eq. (1) denote region and time, respectively. The dependent variable Y_{it} is the carrot seed yield in the model, and the abbreviations of all the climatic explanatory variables used in the model are illustrated in Table 1. α_i represents the fixed effect summarizing time-invariant individual-specific heterogeneity, while ε_{it} indicates the error term. β_0 is the constant term, whereas β_1 to β_{24} denote the estimated coefficients for different independent variables. Previous literature stated that the effects of precipitation and temperature are mostly nonlinear (Konduri et al., 2020; Mishra et al., 2017). Therefore, the quadratic terms of T_{max}, T_{min} and precipitation were included in the statistical model along with the linear terms. Due to the presence of both linear and quadratic terms, a direct interpretation of single model coefficients may not be straightforward. Therefore, marginal coefficients of T_{max}, T_{min} and precipitation of different phenological phases were calculated at their mean values to determine the effect of climatic variables on carrot seed yield (Sharma et al., 2022).

Table 1
Description of considered variables in the panel model.

	Phenological phase	Months	Variables considered	Notation
Vegetative growth	Juvenile • Vegetative growth	Feb- May	Minimum Temperature	JT_{min}
			Maximum Temperature	JT_{max}
			Precipitation	J_{pre}
	Vernalization • Transition from vegetative to reproductive phase	Jun- Aug	Minimum Temperature	VT_{min}
			Maximum Temperature	VT_{max}
			Precipitation	V_{pre}
Reproductive growth	Floral development • Induction of shoot meristem • Induction of flower meristem • Floral organ development	Sep-Dec	Minimum Temperature	FDT_{min}
			Maximum Temperature	FDT_{max}
			Precipitation	FD_{pre}
	Flowering and seed development • Pollination and fertilization • Seed formation and development • Seed harvesting	Jan-Mar (Following Year)	Minimum Temperature	FLT_{min}
			Maximum Temperature	FLT_{max}
			Precipitation	FL_{pre}
	Response variable		Carrot seed yield	Y

2.3. Diagnostic tests

As a prerequisite to the panel data analysis, a set of diagnostic tests were conducted to confirm model assumptions. Non-stationary data (including a unit root) is unexpected and cannot be predicted or modeled. The results acquired using non-stationary time series could be fictitious, implying a relationship between two variables where none exists (Sarker et al., 2014). Since the carrot seed panel dataset is made up of 18 years of observation, the time series data of each variable were checked to determine the presence of unit root (non-stationary) by performing Augmented Dickey-Fuller (ADF) test (Maddala and Wu, 1999), which is recommended to analyse unbalanced panel data set (Dimitrios et al., 2016).

Furthermore, the existence of heteroskedasticity may hinder the robustness of regression model results. Uniformity in the residual scattering across the regression line in a residual plot indicates homoscedasticity (Abbott et al., 1994). The Breusch-Pagan test was performed to check for heteroscedasticity (Breusch and Pagan, 1979). The occurrence of strong correlations between independent variables makes it difficult to determine how each independent variable affects the dependent variable. Furthermore, panel data model estimation will be overfitted if the explanatory variables are correlated, which will lead to biased results. Therefore, a correlation matrix was used to study the relationship between the variables (Hysa et al., 2020; Jelonik et al., 2019). One of the assumptions of linear regression is the absence of autocorrelation, implying residuals are independent of one another. In the presence of positive autocorrelation, the actual standard error is underestimated by the estimated standard errors (Das, 2019). The Durbin-Watson test suggested by Bhargava et al. (1982) was performed to assess the presence of autocorrelation. The Hausman test (Hausman,

1978) was used to identify whether a fixed or random effect model is a probable fit for the panel data. The Hausman test determines if the estimators for fixed effects and random effects are significantly different, as well as the orthogonality between the random effects and the regressors (Hsiao, 2014). The collected data and estimated model were analysed with RStudio (version 2022.07.2 + 576).

3. Results and discussion

3.1. Descriptive statistics of variables

The summary statistics of variables included in the estimations are presented in Table 2. The average harvested carrot seed yield was recorded as 337.3 kg/ha. Due to the failure of the crop during some of the production seasons, the minimum yield was reported as zero. According to the historical climatic data, temperature and precipitation exhibited a significant variation across the different growth phases of carrot seed crops. The juvenile phase of the carrot begins from seed germination (Mandel and Brunet, 2019). Temperature above 30 °C reduced the germination of carrot seeds. Germination completely stopped in the temperature range from 40 °C to 45 °C (Corbineau et al., 1995; Pereira et al., 2007). In regards to physiological activities, Thiagarajan et al. (2007) found that the rate of net photosynthesis reduced by 23.7 % and transpiration increased by 118.9 % when increasing the temperature from 20 °C to 30 °C. The findings confirmed that the temperature ranges from 8.15 °C to 19.30 °C during the juvenile phase have a beneficial influence on seed germination and physiological activities in New Zealand's carrot-growing regions. Also, Wurr et al. (1998) observed that the fresh weight of carrot roots increased along with temperature increment up to 15.5 °C, before declining at a higher temperature. The findings of this study showed that the mean temperature during the juvenile phase is 13.73 °C ($[JT_{min} + JT_{max}] / 2$), which is several degrees lower than 15.5 °C and favourable for the growth of the roots. Additionally, dry conditions due to a lack of soil moisture and fewer intense rainfall events can impact carrot germination, seedling growth, photosynthesis, and transpiration processes (Andriamparany et al., 2020; Schmidhalter and Oertli, 1991; Thiagarajan et al., 2008). Comparatively, the second-highest amount of precipitation was seen during the plant's juvenile stage, confirming that carrots need to have access to soil moisture during their early growth phases (Dellow et al., 2016; Jagosz et al., 2019).

New Zealand mostly uses biennial cultivars to produce carrot seed. The optimum requirement of cold temperature for successful vernalization is 5 °C for 11 to 12 weeks (Linke et al., 2019). This requirement is important for the induction of floral formation via the incremental increase in gibberellic acid within the plant (Nieuwhof, 1984; Ou et al., 2017). The findings (Table 2) showed that vernalization occurred from June to August (Southern Hemisphere's winter months), coinciding with a mean temperature of about 7 °C ($[VT_{min} + VT_{max}] / 2$); this temperature is beneficial for the successful vernalization and, consequently, flower development (Atherton et al., 1990). Carrot flower development begins with the formation of a floral stalk (bolting), followed by the production of involucral bracts and umbel primordia (Hiller and Kelly, 1985; Linke et al., 2019). Quagliotti (1967) observed a significant decrease in flower stalk development when increasing the temperature from 14 °C to 26 °C. Elballa and Cantliffe (1996) noted that the increasing temperature from 17/12 to 33/28 °C reduced the total number of umbels per plant by 44 %. However, according to the historical temperature data, 12.91 °C ($[FDT_{min} + FDT_{max}] / 2$), the temperature that prevailed during the time of carrot flower development is suitable for the floral stalk development and umbel formation.

The carrot pollination process has also been affected by environmental impacts (Gaffney et al., 2018; Howlett, 2012). Previous studies showed that the warmer temperature (30 °C) reduced the receptive period of stigma, which can negatively affect the fertilization process (Chira et al., 2008). Furthermore, Broussard et al. (2017) suggested that increasing temperatures may have an impact on carrot flower attributes that attract pollinators, including nectar concentration and volatile emission. Pollinators' subsequent foraging behavior may be impacted as a result of this. Elballa and Cantliffe (1996), also reported that exposing carrot seed crops at anthesis or before seed development to a warm temperature (33/28 °C) could adversely affect the seed yield and seed quality of carrots. Whereas the seeds produced at 20/15 °C exhibited comparatively higher progeny vigour and germination than seeds formed and developed at 33/28 °C. However, the minimum (10.87 °C) and maximum (22.37 °C) temperature that existed during the flowering and seed development phase, is appropriate for the pollination, fertilization, and production of high-quality carrot seeds. Moreover, this phase overlaps with the warmest and driest season in New Zealand. Comparatively less precipitation, 163.50 mm (see Table 2), at the time of the flowering and seed development phase compared with the other phases, will minimize fungal and bacterial infections during the flowering and seed development (Deleuran and Boelt, 2009).

Table 2
Descriptive statistics on yields and climate variables (2005–2022).

Variables	Unit	Mean	Std.Dev	Maximum	Minimum
JT_{min}	°C	8.15	1.28	11.73	4.45
JT_{max}	°C	19.30	1.49	22.78	16.38
J_{pre}	mm	236.90	90.33	518.90	78.20
VT_{min}	°C	2.21	1.26	4.73	−1.23
VT_{max}	°C	12.23	1.58	15.70	8.37
V_{pre}	mm	190.50	77.70	421.90	47.50
FDT_{min}	°C	7.38	1.21	10.48	3.530
FDT_{max}	°C	18.44	1.34	21.55	16.23
FD_{pre}	mm	240.60	88.13	512.90	77.20
FLT_{min}	°C	10.87	1.44	15.90	7.67
FLT_{max}	°C	22.37	1.55	25.73	19.50
FL_{pre}	mm	163.50	76.80	453.00	40.20
Y	kg/ha	337.30	260.58	1080.80	0.00

Std.Dev- Standard deviation.

3.2. Pre-estimation diagnostic tests

A correlation matrix of the variables used in the panel model is shown in Fig. 1. Hysa et al. (2020) claimed that the initial indication of significant multicollinearity is the presence of a very high correlation between the variables, which is typically considered to be 0.85–0.90 or greater. The results of the estimated correlation (Fig. 1) revealed that there was no problematic correlation between the variables. Table 3 shows the results of the

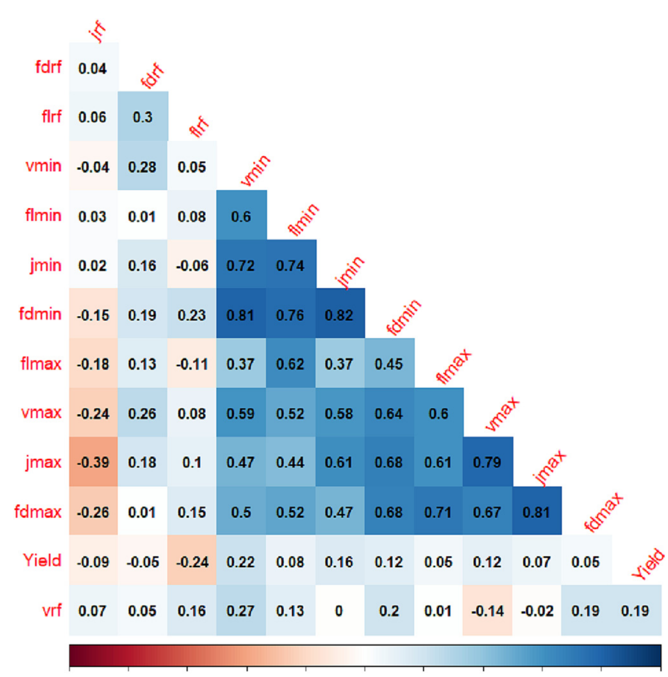


Fig. 1. Pearson correlation matrix of variables.

Table 3
Results of unit root test.

Variables	Augmented Dickey-Fuller Test			
	With trend		Without trend	
	Test statistics	*p*-value	Test statistics	*p*-value
JT_{max}	−3.590	0.000	−0.450	0.000
JT_{min}	−4.117	0.000	−0.523	0.009
J_{pre}	−5.291	0.000	−1.181	0.000
VT_{max}	−2.805	0.000	−0.632	0.001
VT_{min}	−3.480	0.000	−1.568	0.005
V_{pre}	−6.457	0.000	−1.181	0.000
FDT_{max}	−3.965	0.000	−0.361	0.000
FDT_{min}	−4.466	0.000	−0.691	0.016
FD_{pre}	−4.583	0.000	−1.013	0.000
FLT_{max}	−3.485	0.000	−0.234	0.000
FLT_{min}	−4.489	0.000	−0.447	0.025
FL_{pre}	−7.899	0.000	−1.543	0.000

Augmented Dickey-Fuller (ADF) unit root test. According to the estimated test statistics, climate and carrot seed yield variables reveal similar results with and without a time trend. Furthermore, this implies that, for all variables in the table, the null hypothesis of unit roots (i.e., non-stationary) is rejected at the 5 % level of significance. The conclusion is that all the variables are stationary, and that differencing is redundant. As shown in Table 4, the panel model had a *p*-value of 0.7735 for the Breusch–Pagan–Godfrey test, which was not statistically significant ($p > 0.01$) and revealed that the null hypothesis of homoscedasticity can be accepted. Furthermore, the result of the Durbin-Watson test (2.4) proved the lack of serial correlation in the model (Table 4). This conclusion was made by incorporating the suggestion of Field (2009), who stated that values of the Durbin-Watson test statistic from 1 to 3 are relatively normal. Based on the Hausman test results (Table 4), the fixed effect model was selected for the model estimation by rejecting the null hypothesis (H_0: random effects model is suitable, H_a: random effects model is not suitable) at 1 % significance level (Hausman, 1978).

Here Fig. 1.

3.3. Observed climate trends across carrot seed crop-growing regions in New Zealand

The observed climatic trends are shown in Fig. 2. Throughout the carrot seed crop growing season (CSGS), the T_{max} and T_{min} showed a similar increasing trend. This is further validating the warming trends already reported for New Zealand (Ministry for the Environment and Stats NZ, 2020). By the middle of the 21st century, the New Zealand region's mean air temperature is predicted to have increased by +1.0 °C compared with 1995–2014, and by 2100, it is predicted to have increased by +1.6 °C under Shared Socioeconomic Pathways (SSPs) 2–4.5. In the middle and at the end of the century, the expected increases in mean air temperature for SSP5–8.5 are +1.3 °C and +3.1 °C in comparison with 1995–2014, respectively (Bodeker et al., 2022). Furthermore, precipitation has exhibited an increasing pattern during the reproductive stages (floral development, and flowering and seed development phases) and a decreasing trend during vegetative ones (juvenile and vernalization phases) over the past 18 years in New Zealand. These findings were further supported by Ministry for the Environment (2018), which stated that projected changes in precipitation exhibit a clear seasonality and regional variability in New Zealand. Furthermore, all climatic variable trends were found to be significant ($p < 0.01$), except for precipitation ($p = 0.3914$) during the vernalization phase in CSGS.

Table 4
Results of model specification tests.

Specification tests	Value
Heteroscedasticity tests	
Breusch–Pagan–Godfrey test	18.589
(p-value)	0.7735
Serial correlation test	
Durbin–Watson test statistic	2.4
(p-value)	0.9907
Hausman test (fixed effect vs random effect)	
Chi-square value	49.459***
(*p*-value)	<0.001

*** Specifies that the significance at 1 %; Breusch–Pagan–Godfrey test indicates the F-statistic.

Table S 1 indicates the annual rate of change in climatic variables. The values of maximum and minimum temperature, and rainfall varied throughout the juvenile phase of the CSGS by 0.2 °C (T_{max}), 0.134 °C (T_{min}), and −6.508 mm, while during vernalization, they changed by 0.254 °C, 0.168 °C, and −1.105 mm. Moreover, the rate of changes in T_{max} (0.147 °C), T_{min} (0.180 °C) and precipitation (5.041 mm) at the floral development stage increased significantly ($p < 0.01$) over time. During the flowering and seed development phases, the rate of changes in maximum and minimum temperatures and precipitation were respectively 0.159 °C, 0.165 °C and 3.508 mm, from 2005 to 2022. In accordance with Ministry for the Environment (2018), the study area is on the east of both islands, which includes Hawke's Bay and Canterbury, where conditions are likely to be wetter (increasing trend) during the summer (flowering and seed development phase) and drier (decreasing trend) during winter (vernalization phase). The phenological phases of vernalization, floral development, and juvenile, accordingly, were associated with the largest rates of changes in T_{max}, T_{min}, and precipitation.

Commonly, it is believed that the temperature and precipitation changes have a significant influence on seed germination (Corbineau et al., 1995; Pereira et al., 2007), seedling establishment (Ibrahim et al., 2006), vernalization (Atherton et al., 1990), taproot development (Gomes et al., 2020; Zeipiņa et al., 2014), photosynthesis (Thiagarajan et al., 2012), floral development (Samuolienė et al., 2008), pollination (Broussard et al., 2017), and seed formation (Gray et al., 1988; Hooda et al., 2013) in carrots. Furthermore, the activities of pollinators have also been altered by these climatic factors (Howlett, 2012). Based on these long-term trends in weather variables, T_{max}, T_{min}, and precipitations can influence carrot seed production during the growing season in New Zealand by altering the physiological and flowering processes. To mitigate changes in weather variables, multiple responses will be essential, including development and introduction of new varieties through plant breeding strategies, geographic shifts, and adapting climate-smart agronomic practices (Franke et al., 2022; Vandamme et al., 2022; Xiong et al., 2022).

3.4. Effect of changes in temperature and precipitation on carrot seed yield

The estimates of the influence of seasonal temperature and precipitation on carrot seed yield by using the fixed effect model are presented in Table 5.

In general, the juvenile phase of carrots includes seed germination and vegetative growth along with leaf and taproot development (Geoffriau and Simon, 2020). During the juvenile phase of carrot seed crops, the regression coefficient of JT_{min} was shown to be negative and significant. Whereas the quadratic term of JT_{min} exhibited a significant positive trend. Moreover, the study results illustrated that the JT_{max} had a beneficial effect on carrot seed yield, while the effect of JT^2_{max} was found to be negative and significant on the seed production of carrots. These findings indicated that the trend of maximum and minimum temperature is nonlinear during the juvenile stage of carrot seed crops, which agrees with a recent similar maize and cotton study (Sharma et al., 2022). The higher temperature can interrupt the metabolic and enzymatic activities held during germination (Dias et al., 2015; Nascimento et al., 2008). Moreover, the reduced germination due to the increase in temperature stress during the germination period may result in heterogeneous growth in plants along with substandard emergence, which could cause variation in the maturity of the seed crops. Carrot is an indeterminant crop and therefore flowers continuously. A narrow flowering time is crucial for high yields of seeds with the same maturity.

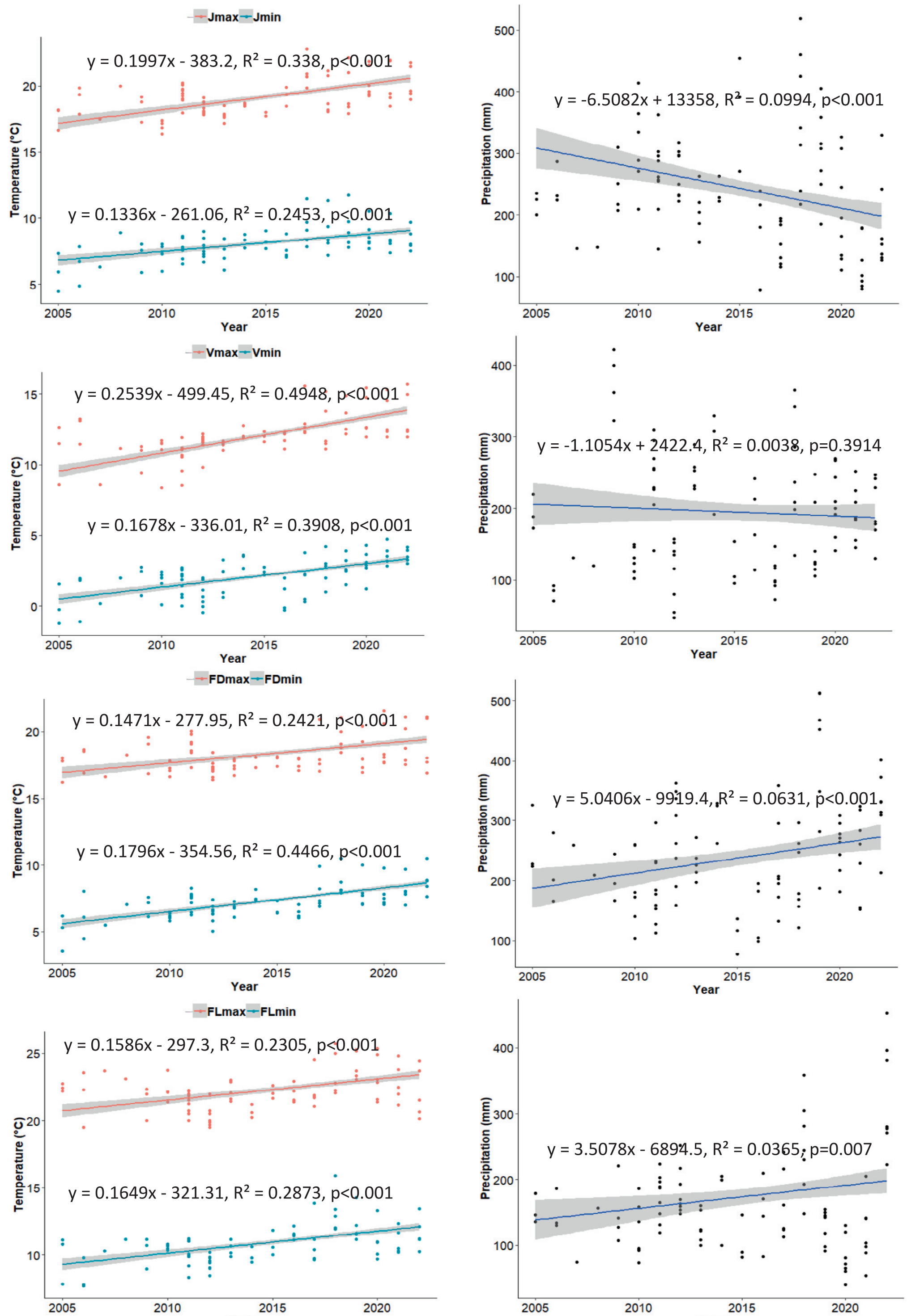


Fig. 2. Temperature and precipitation during the different phenological phases. (A) and (B)- juvenile phase (Feb to May); (C) and (D)- vernalizing phase (Jun to Aug); (E) and (F)- floral development phase (Sep to Dec); (G) and (H)- flowering and seed development phase (Jan to Mar - following year).

Ultimately, the quality of the seed harvested will be reduced by uneven production in the field due to uneven maturity (Nascimento et al., 2008; Tetteh et al., 2018). Moreover, Hussain et al. (2008) noted that a temperature increase beyond 20 °C can result in a decline in plant vegetative matter during the juvenile phase, which has a significant impact on the production of carrot seeds. Likewise, increasing temperature beyond 25 °C has a commensurate increase in the rate of respiration with resultant poor root yield (Rubatzky et al., 1999). Reduced root size (yield) typically results in less food storage, which will potentially impact seed development and seed production (Ilyas et al., 2013). The negative (J_{pre}) and positive (J^2_{pre}) signs of the precipitation coefficients have shown that rainfall during the juvenile phase of carrot seed crop has a significant ($p < 0.01$) U-shaped relationship with carrot seed yield, that is, as rainfall increases, carrot seed yield decreases, but only up to a certain point after which it starts increasing. This may be due to the varying degrees of sensitivity of different sub-phases (germination, seedling establishment, and root development) of the

Table 5
Panel regression results for carrot seed yield response.

Variables	Regression Coefficient	Standard error	t-value	*p*-value
JT_{max}	1403.100*	801.74	1.750	0.086
JT^2_{max}	−39.634*	21.31	−1.860	0.069
JT_{min}	−1362.600***	401.58	−3.393	0.001
JT^2_{min}	84.507***	24.50	3.449	0.001
J_{pre}	−4.801***	1.67	−2.876	0.006
J^2_{pre}	0.008***	0.00	2.683	0.010
VT_{max}	−188.420	595.09	−0.317	0.753
VT^2_{max}	13.133	25.49	0.515	0.609
VT_{min}	168.990	153.38	1.102	0.276
VT^2_{min}	−80.892***	29.40	−2.752	0.008
V_{pre}	4.117**	2.04	2.019	0.049
V^2_{pre}	−0.007	0.00	−1.596	0.117
FDT_{max}	−134.060	1029.00	−0.130	0.897
FDT^2_{max}	4.492	27.87	0.161	0.873
FDT_{min}	441.980	406.84	1.086	0.282
FDT^2_{min}	−17.687	27.64	−0.640	0.525
FD_{pre}	1.278	1.40	0.915	0.364
FD^2_{pre}	−0.003	0.00	−1.248	0.218
FLT_{max}	181.010	889.48	0.204	0.840
FLT^2_{max}	−4.258	20.36	−0.209	0.835
FLT_{min}	567.630*	321.34	1.766	0.083
FLT^2_{min}	−29.448**	14.55	−2.023	0.048
FL_{pre}	−2.711	1.66	−1.638	0.108
FL^2_{pre}	0.003	0.00	0.817	0.418

* Specify that the significant at the 10 %.
** Specify that the significant at the 5 %.
*** Specify that the significant at the 1 %.

juvenile stage to precipitation. Deficits in soil moisture can reduce the germination of seeds and seedling emergence by altering the imbibition rate, delaying the mobilization of food reserves and metabolic activities in the germinating seed, and inhibiting plumule and radicle elongation. Consequently, delayed germination and seedling growth could result in poor root growth (Lada et al., 2004) and, in turn, reduced seed production. For uniform seedling emergence, it is beneficial for the optimum precipitation to coincide with the radicle initiation and seed germination times (Finch-savage and Phelps, 1993). On the other hand, excessive rainfall or flooding can lower the amount of oxygen that is available in the soil profile, which causes stress for seed germination and seedling emergence (Zhou et al., 2020). Previous studies have shown that when the drought has prevailed for 10 days, the carrot seedlings reach their permanent wilting stage. Furthermore, 7 days of drought reduced the soil moisture by 43 %, which increased the xylem pressure potential by 67 % approximately (Rajasekaran and Blake, 2002). These effects, individually or combined, are likely to lower the yield of carrot seeds.

Climatic factors play a key role in the transition from the vegetative stage to the reproductive stage via vernalization by initiating various changes to the morphological and physiological processes in carrots (Alessandro et al., 2013; Liu et al., 2020; Siswadi et al., 2021). The results (see Table 5) illustrated that the VT_{max} and VT^2_{max} are not significant ($p > 0.1$). While only the VT^2_{min} had a significant ($p < 0.01$) and negative influence on the carrot seed yield. This finding is in accordance with the results of Atherton et al. (1990), who reported that increments of temperature from −1 °C to 5 °C increased flowering of carrots, while a significant decline was observed when increasing the temperature from 7 °C to 16 °C. In New Zealand, vernalization of carrots occurs from June to August, the three coldest months (Abrahim et al., 2022; Pole, 2003). This is one of the key reasons for the nonsignificance of vernalization temperature (VT_{max} and VT_{min}) on carrot seed yield. The overall 18-year averaged VT_{max}, 12.23 °C and VT_{min}, 2.21 °C (see Table 1) fall under the values of 14.6 °C and 6.6 °C, which are considered as the ceiling values for maximum and optimum temperature, for the vernalization of carrot (Weikai and Hunt, 1999). The impact of precipitation during the vernalizing phase has been found to be beneficial ($p < 0.05$), whereas the quadratic term is negative and not significant ($p > 0.1$). This suggests that the result is linear. However, any damage caused due to the excess precipitation at the time of vernalization is minimal to carrot seed yield because the plant is still in the vegetative phase. A similar effect on the linear and squared term of rainfall was reported for the productivity of pigeon peas in India (Mishra et al., 2017) and Aus-type rice in Bangladesh (Sarker et al., 2014). Reid and Gillespie (2017) observed that increasing soil water deficit reduced storage root fresh yield of carrot cv Chantenay Red Core by (0.30 ± 0.025) t ha^{-1} mm^{-1} in New Zealand. Root size is an influencing factor on carrot seed yield (Ilyas et al., 2013). Similarly, previous studies showed that the soil moisture level below −60 cbar significantly reduces root yield. This reduction could be due to the dysfunction of physiological activities under water stress conditions (Lada and Stiles, 2014). These findings indicated that the soil moisture deficit, even during vernalization can alter the size of the taproot, which ultimately affects the carrot seed yield (Kumar et al., 2017).

There was no significant ($p > 0.1$) relationship between carrot seed yield, and maximum temperature (except FLT_{min} and FLT^2_{min}) and precipitation during floral development and flowering and seed development (both in linear and quadratic terms) (see Table 5). This could be due to the presence of optimum maximum temperature and precipitation during floral development, pollinator activities, fertilization, and seed development throughout the reproductive phase from 2005 to 2022. However, this situation could change due to predicted future climate change. Whereas FLT_{min} and FLT^2_{min} variables have exhibited a significantly positive and negative effect on carrot seed yield, respectively (see Table 5). Increasing temperature is detrimental to carrot seed production due to its adverse effect on the pollination process, altering the growth, development and performance of plant reproductive parts, flower reward production and foraging activities of pollinators (Descamps et al., 2018; Ramírez and Kallarackal, 2018; Thakur et al., 2010). Most early studies revealed that increments of temperature from 20/10 °C to 30/20 °C significantly reduced the average weight of a single seed. Although the weight of the embryo and endosperm has not been affected, the pericarp weight decreased with increasing temperature (Gray et al., 1988), again reducing yield. In New Zealand, Broussard et al. (2017) studied the effect of increasing temperature on hybrid carrot seed production and discovered that increasing temperature reduced the volatile production and increased the concentration of nectar sugar, which may minimize the attractiveness of insect pollinators.

3.5. Marginal effects

The average marginal effects of a 1 °C rise in temperature and of a 1 mm increase in rainfall (Birthal et al., 2014) on carrot seed yield are shown in Table 6.

The average marginal effect of JT_{max} was shown to be negative and significant ($p < 0.1$) during the CSGS, indicating a 126.76 kg/ha decrease in carrot seed yield for every 1 °C increase in its value. As suggested by Hussain et al. (2008), carrot is highly sensitive to temperature rise during photosynthesis, and root and plant partitioning, which can negatively affect

Table 6
Marginal effects of climatic variables on carrot seed yields.

Variables	Marginal coefficient of regression	Standard error	z- value	*p*-value
JT_{min}	14.820	82.608	0.179	0.858
JT_{max}	−126.760*	72.779	−1.742	0.082
J_{pre}	−1.038**	0.521	−1.991	0.046
VT_{max}	132.728*	77.970	1.702	0.089
VT_{min}	−187.724**	81.041	−2.316	0.021
V_{pre}	1.327**	0.553	2.399	0.016
FDT_{max}	31.629	68.799	0.460	0.646
FDT_{min}	180.832*	97.791	1.849	0.064
FD_{pre}	−0.119	0.550	−0.215	0.829
FLT_{max}	−9.575	61.717	−0.155	0.877
FLT_{min}	−72.640	58.749	−1.236	0.216
FL_{pre}	−1.745***	0.663	−2.630	0.009

* Specify that the significant at the 10 %.
** Specify that the significant at the 5 %.
*** Specify that the significant at the 1 %.

seed production. The average marginal effect of JT_{min} had no significant ($p > 0.1$) effect on the seed yield of carrots. This shows that the minimum temperature at the juvenile stage of the CSGS is generally favourable for the growth and development of carrots and their seed production. Moreover, it was determined that the MCR of J_{pre} was unfavourable ($p < 0.05$), resulting in a reduction of 1.038 kg/ha in carrot seed production for every increase in rainfall of 1 mm. A 1 °C rise in VT_{min} significantly dropped the carrot seed yield by 187.724 kg/ha. In contrast, VT_{max} positively and significantly influenced the seed yield by increasing it by 132.728 kg/ha for each 1 °C increment. Similarly, carrot seed yield benefitted significantly from the rise in V_{pre}, where an increase in 1 mm rainfall has boosted the seed yield by 1.327 kg/ha. Carrot seed crop shows a statistically significant increase in seed yield during the floral development phase when increasing the minimum temperature (FDT_{min}), i.e., 180.832 kg/ha increase in seed yield with a 1 °C increase in FDT_{min}. Hiller and Kelly (1979) noted that an increase in post-vernalization (6 weeks) temperature to 27/32 °C affected floral stalk elongation in carrots, though the floral differentiation has not been affected adversely. Similar observations were reported by Elballa and Cantliffe (1996), who found an increase in day/night temperature from 17/12 °C to 33/28 °C decreased flower stalk height and number of umbels per plant from 73 cm to 55 cm and 50 to 28, respectively. However, over the past 18 years of CSGS, the minimum and maximum temperatures during floral development ranged from 3.53 °C to 10.48 °C and 16.23 °C to 21.55 °C, respectively (see Table 2), which are far below the ceiling limit for the destruction of flower organs. This could be one of the reasons for the positive relationship between FDT_{min} and carrot seed yield. The average marginal effect of FDT_{max} and FD_{pre} are statistically not significant for carrot seed yield. The marginal effects of FLT_{max} and FLT_{min} have been found to be negative, though non-significant ($p > 0.1$). With a decrease of 1.745 kg/ha for every 1 mm, FL_{pre} has had a negative and significant ($p < 0.01$) impact on carrot seed production. This result agrees with Lawson and Rands (2019), who show that changes in rainfall pattern cause nectar dilution, pollen degradation and affects pollinator activities.

The marginal effects analysis indicated that precipitation has a significantly (except for FD_{pre}) lower marginal effect than minimum and maximum temperature. A similar trend was observed by Mishra et al. (2017) on pigeon peas and by Sharma et al. (2022) on cotton and soybean. The highest unfavourable effect from precipitation has been reported at the flowering and seed development phase, while only the vernalization phase is favoured by the precipitation compared with other phases.

4. Conclusion

The main objective of this study was to evaluate the effects of changes in minimum temperature, maximum temperature, and precipitation on the seed yield of carrots using an unbalanced panel data model. Based on the results of diagnostic tests, a fixed effect model was utilized to estimate the impacts. The use of fixed effect model is appropriate because it accounts for all time-invariant omitted variables in the model. Historical climatic data highlighted the increasing trends in the rate of changes in minimum and maximum temperature in the eastern region of both the North and South Islands of New Zealand, where carrots are grown for seed production, throughout the season. The rate of changes in precipitation was negative during the vegetative (February to August) and positive during the reproductive (September to March) stages of carrot seed growth. These patterns have value for the prediction and mitigation of future extreme climatic effects on carrot seed production. Consistent with the existing results, increasing rainfall was found to be unfavourable to the seed yield throughout the phenological stages except during vernalization. On the other hand, the rising pattern of maximum temperature during the juvenile phase, and flowering and seed development exhibited a negative effect on carrot seed yield. A 1 °C rise in maximum temperature at vernalization and floral development is estimated to be beneficial. Meanwhile, the increment of minimum temperature over juvenile and floral development has an advantageous effect on seed yield. In contrast, a 1 °C rise in minimum temperature at vernalization, and flowering and seed development was found to be detrimental to seed production. These results lead to the conclusion that the degree to which temperature and rainfall affect carrot seed yield depends on the different phenological stages and on whether they are minima or maxima. Meanwhile, marginal effects of maximum and minimum temperatures are having a higher impact on carrot seed yield. Furthermore, it is clear that the growth and development, and physiological activities beginning from seed germination to harvest influence carrot seed yield. These suggest the importance of formulating and adapting phenological stage-specific climate change strategies to cope with future climate change. This work further offers data for important policy choices, such as the development of climate-resilient carrot seed crops via biotechnological techniques, identifying possible carrot seed production sites, and adaptation of precision agriculture practices in response to climate change.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164502.

CRediT authorship contribution statement

Asharp Godwin: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Craig McGill:** Conceptualization, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Andrew Ward:** Conceptualization, Supervision. **Svetla Sofkova-Bobcheva:** Conceptualization, Writing – review & editing, Supervision. **Simone Pieralli:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision.

Data availability

I have shared the sources of the data

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.

Acknowledgement

Authors are grateful to Accelerating Higher Education Expansion and Development (AHEAD) Project (launched by the Sri Lankan Government under the World Bank fund), Seed Industry Research Centre (SIRC), AsureQuality Ltd., and School of Agriculture and Environment, Massey University for research and scholarship funding. Special thanks to South Pacific Seeds New Zealand Ltd. and Richard van Garderen who provided the historical carrot seed yield data for the study.

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