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Effects of Abiotic Stress Associated with Climate Change on Potato Yield and Tuber Quality Under a Multi-environment Trial in New Zealand

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Abstract

In the 2018/19 growing season, a multi-environment trial in Opiki, Hastings, and Ohakune located in three different regions of the North Island of New Zealand was conducted to evaluate responses of selected potato cultivars to abiotic stress associated with climate change. Heat and drought stresses were evident with supra-optimal temperatures (>25 °C) in Opiki and Hastings and sub-optimal rainfall (<500 mm) in Opiki, which influenced the different morpho-physiological characteristics of the potato crop, ultimately affecting yield and tuber quality. These abiotic stresses also increased the incidence of malformation, growth cracks, and second growth in tubers reducing the total and marketable tuber yields by 43% and 45%, respectively. In addition, the genotype × environment analysis showed that Ohakune had the most favourable environmental conditions for potato production since all cultivars in this site had superior marketable tuber yields. 'Taurus' was the most stable and adaptable cultivar across trial sites (wide adaptation), whilst 'Hermes' and 'Snowden' were more adapted under Opiki and Hastings conditions (specific adaptation), respectively. As established in this study, heat and drought stresses have significant effects on the morpho-physiology, yield, and tuber quality of commercial potato cultivars in New Zealand.

Keywords Climate adaptation · Drought stress · Genotype · Heat stress · Marketable tuber yield · Physiological disorders

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Introduction

Potato (*Solanum tuberosum* L.) is an economically important vegetable crop grown in over 150 countries. It ranks fifth after sugarcane, maize, wheat, and rice as main crops in terms of production volume (FAO 2022). In New Zealand, potato is the top vegetable crop based on production area (10,901 ha), production volume (554,052.53 MT), and export value ($110 million) (FAO 2021). However, the New Zealand potato industry is faced with many challenges such as stringent government policies, high production costs due to the economic impacts of the global pandemic, and extreme weather events (Potatoes New Zealand 2022). Amongst these challenges, the extreme weather events, e.g., droughts, heatwaves, and flooding, often associated with climate change are gradually impacting potato production in New Zealand.

In general, potato production under climate change is expected to decline by 18–32% (without adaptations) and by 9–18% (with adaptations) (Hijmans 2003). The influence of environment, in the genotype × environment interaction, plays a significant role in the yield variation of potato crops. Agro-meteorological factors significantly contribute to the variability of potato crop yields under experimental (20–60%) (Kalbarczyk 2004) and field (40–80%) conditions (Kalbarczyk 2004; Trawczyński 2009).

In New Zealand, the western and southern regions are anticipated to receive more rain and experience warmer temperatures, whilst eastern and northern regions will experience double to triple the frequency of drought episodes by 2040 (New Zealand Agricultural Greenhouse Gas Research Centre 2012). In a 60-year (1958–2018) climate data analysis in selected potato-growing areas in New Zealand (Siano et.al. 2018), atmospheric temperature and rainfall showed an increasing and decreasing trend, respectively, which are consistent with reports from the Ministry of Environment (2016) and the IPCC (2014).

Before releasing a cultivar, genotypes of high potential are typically evaluated at different locations and over several years to determine their degree of adaptation (Acquaah 2012). However, in most cases, a thorough assessment of adaptation and yield stability characteristics of these cultivars is lacking before their recommendation (FAO 2002). The multi-environment trial (MET) is a practice used to evaluate crops over multiple locations to identify superior cultivars (Acquaah 2012). The main effects of the environment (E), genotype (G), and associated G × E interaction are determined using appropriate statistical systems. Through MET, yield can be estimated, and stable cultivars in different environments can be identified (Crossa 1990). MET is often used as a tool for selecting superior genotypes for planting in new sites. In potatoes, MET has been applied in testing and screening for improved tuber yield and disease resistance (Paget et al. 2014). This study aimed to evaluate the performance of selected commercial potato cultivars, through MET, as affected by abiotic stresses in different regions in the North Island of New Zealand.

Materials and Methods

Site Description and Local Climate

The multi-environment trial (MET) was established in the summer of 2018/19 in three commercial potato farms located in three regions (different ecozones) of the North Island of New Zealand i.e., Ohakune (39.500 ° S, 175.459 ° E, 593 m above sea level (masl), central North Island), Opiki (−40.465 ° S, 175.481 ° E; 3 masl; southwest North Island), and Hastings (−39.624 ° S, 176.738 °E; 17 masl; eastern North Island). The Ohakune site is a conventional-irrigated farm, ex-pasture, orthic allophanic-volcanic ash soil (Landcare Research 2020), with an average temperature of 10.2 °C and average annual rainfall of 1500 mm. The Opiki site is a conventional-rainfed farm, ex-pasture, humic organic soils (Landcare Research 2020), with an average temperature of 13.2 °C, and average annual rainfall of 990 mm. The Hastings site is an organic-irrigated farm, ex-cover crop, mottled fluvial recent soil-alluvial sand silt or gravel soil (Landcare Research 2020), with an average temperature of 14.0 °C and average annual rainfall of 770 mm.

Crop Management and Trial Layout

Five offshore-bred potato cultivars—'Agria' (reference cultivar), 'Hermes', 'Fianna', 'Taurus', and 'Snowden'—and two New Zealand-bred potato cultivars—'Rua' and 'Ilam Hardy'—from certified seed suppliers were used in the trial. The experimental setup was a Randomized Complete Block Design with four blocks and cultivars were fully randomized in each block. Pre-sprouted seed potatoes 40–60 mm in diameter were manually planted in ridged rows 12 m long with between and within row spacing of 100 and 30 cm, respectively. The grower's cultural management practices in each site, including land preparation, nutrient and water management, and pest and disease management, were adopted to simulate local growing practices. In the Hastings trial site, being an organic farm, a nylon mesh cover (0.6 mm pore size) was used as a physical barrier to exclude the tomato–potato psyllid (TPP) (*Bactericera cockerelli*), which is the insect vector of *Candidatus Liberibacter solanacearum* that causes zebra chip in potatoes.

Weather Data

The atmospheric temperature was recorded using a temperature logger DS1921G-F5# Thermochron (www.maximintegrated.com) in Opiki and Harvest Air Temperature Sensor (Harvest Electronics NZ Ltd.) in Hastings. The atmospheric temperature in Ohakune and the soil temperature and daily rainfall (within a 15-km radius of the trial sites) in all sites were obtained from CliFlo—New Zealand's web-based national climate database. The accumulated growing degree days (GDD) at 4.4 °C base temperature was calculated using the CIP (2013) formula.

Agronomic and Morpho-physiological Data

At 65 days after planting (DAP), the plant height (mm), stem diameter (mm), and total plant leaf area (cm^2) were recorded. For the total plant leaf area, 10 fully developed leaf sub-samples per plant were randomly selected and weighed, and the leaf area was measured using LI-3100C Leaf Area Meter (LI-COR Biosciences, USA, www.licor.com). The total plant leaf weight was divided by the weight of the sub-samples and multiplied by the measured leaf area to get the total plant leaf area.

The net photosynthesis (μmol CO_2 m^{-2} s^{-1}), transpiration rate (mmol H_2O m^{-2} s^{-1}), and stomatal conductance (mol H_2O m^{-2} s^{-1}) were measured using LI-COR portable photosynthesis system IRGA LI-6400 model (www.licor.com). At the same time, the chlorophyll content (SPAD value) was recorded using a portable chlorophyll metre CCM-200plus (www.optisci.com). All measurements were done on the 3rd or 4th fully expanded leaf from the shoot tip between 1000 and 1400 h, with eight samples measured per cultivar.

Yield and Tuber Quality Data

At 130 DAP, manual harvesting was done at the different sites. The total yield (t ha^{-1}), marketable tuber yield (t ha^{-1}), number of tubers per plant, number of marketable tubers per plant, dry matter content (DMC) (%), harvest index or HI (%), specific gravity (SG), and percentage of tuber physiological disorders were recorded.

Tubers were classified as marketable if within the marketable size standards and with minimal or no defects (physiological disorders) or unmarketable if undersized or had severe to very severe defects. Percent tuber physiological disorders (e.g., malformation, second growth, growth cracks, enlarged lenticels, feathering, and vascular browning) were determined by dividing the number of tubers with physiological disorders over the total number of tubers per plant and multiplying by 100.

Ten randomly selected marketable tubers from each cultivar were used to measure the DMC and SG. The DMC was determined by oven-drying the chopped potato tubers at 70 °C for five days. The fresh and dry weights were measured, and the DMC was calculated by dividing the dry weight by the fresh weight and multiplying by 100. The HI was estimated using the ratio of tuber dry weight: total plant dry weight and multiplying by 100 (MacKerron and Heilbronn 1985). The SG was determined by first weighing the tubers using a top-loading balance (weight in air) and then weighing them whilst suspended in water (weight in water) (Haase 2003). The weight in air was then divided by the difference between weight in air and weight in water.

Statistical Analysis

All the statistical analyses were carried out in R statistical package version 3.4.0 (R Core Team 2017). The significant difference was analysed using Analysis of Variance (ANOVA), and mean values were compared amongst cultivars by using Tukey's HSD test if the overall test was significant.

Genotype × Environment Analysis

The additive main effect and multiplicative interaction (AMMI) method was used, where an integrated ANOVA and principal component analysis (PCA) were applied to analyse the MET (Crossa et al. 1991; Zobel et al. 1988). ANOVA was used to determine the main effects of genotypes and environments and the PCA for the residual multiplicative interaction amongst genotypes and environments. After detecting a significant G × E interaction, the data were graphically analysed by biplot technique to simultaneously classify genotypes and environments (Hongyu et al. 2014; Kempton 1984; Zobel et al. 1988). Through this method, cultivars with high productivity and wide adaptability (wide adaptation), as well as cultivars with specific adaptability (specific adaptation), were identified.

Results

Weather Data

In general, Ohakune had the most favourable weather condition amongst the sites, whilst Opiki and Hastings had more extreme weather conditions during the 2018/19 potato growing season (Table 1). The maximum average atmospheric temperature (AT) in Opiki (25.1 °C) was much higher than the historical average (20.4 °C). Similarly, the number of days with supra-optimal AT i.e., > 25 °C and > 30 °C was highest in Opiki at 103 and 24 days, respectively. Throughout the season from planting (October) to harvesting (February), the average daily maximum AT increased by about 6 °C relative to the historical average. The use of mesh covering in Hastings created a microclimate resulting in about a 2 °C increase in AT. Correspondingly, the number of days with > 25 °C increased by 80% (from 49 to 61 days) and > 30 °C increased by 38% (from 8 to 21 days). In contrast, Ohakune had only 20 days of temperatures > 25 °C and one day of temperature > 30 °C. The increase in AT in Opiki and Hastings resulted in a faster accumulation of growing degree days or GDD (Fig. 1). In the same way, the seasonal average soil temperature (ST) was much higher in Opiki (19.5 °C) and Hastings (19.0 °C) than in Ohakune (15.7 °C). On the other hand, total rainfall was lower by 40% (from 642.1 to 388.0 mm) in Ohakune, by 10% (from 465.8 to 423.0 mm) in Opiki, and by 11% (from 455.4 to 406.0 mm) in Hastings.

Table 1 Weather data in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season

Trial sites/details	Monthly Atm. Temp. (°C)						Ave. Atm. Temp. (°C)	No. of days with supra-optimal Atm. Temp	Soil Temp. (°C)	Total rainfall (mm)	
	Oct	Nov	Dec	Jan	Feb	Mar				Seasonal (2018/19)	Historical Ave. (1981–2010)
Ohakune										388.0	642.1
$Season_{av}$	9.8	11.3	14.6	17.2	15.6	15.1	13.9		15.7		
$Hist_{av}$	9.7	11.6	14.0	15.4	15.4	13.5	13.3				
Max_{av}	15.1	16.9	20.4	23.4	22.4	21.8	20.0		19.8		
$Hist_{av}$	14.2	16.7	19.0	21.2	21.2	18.9	18.5				
Min_{av}	4.5	5.8	8.8	10.9	8.8	8.3	7.9		12.6		
$Hist_{av}$	5.3	6.4	8.9	9.7	9.7	8.1	8.0				
No. of days > 25 °C	0	0	2	10	7	1		20			
No. of days > 30 °C	0	0	0	1	0	0		1			
Opiki										423.0	465.8
$Season_{av}$	13.8	16.0	18.3	19.9	18.4	18.3	17.5		19.5		
$Hist_{av}$	12.5	14.2	16.4	17.8	18.2	16.6	16.0				
Max_{av}	18.1	24.5	26.4	27.3	25.8	24.7	25.1		23.2		
$Hist_{av}$	16.6	18.3	20.6	22.5	22.9	21.2	20.4				
Min_{av}	8.1	9.4	12.3	14.2	11.0	13.4	11.3		16.5		
$Hist_{av}$	8.4	10.0	12.1	13.1	13.5	11.9	11.5				
No. of days > 25 °C	1	18	24	25	19	16		103			
No. of days > 30 °C	0	3	7	9	4	1		24			
Hastings										406.0	455.4
$Season_{av}$	12.1	15.0	17.5	20.1	17.9	17.1	16.6		19.0		
$Hist_{av}$	13.6	15.3	17.7	18.8	18.7	17.1	17.5				
Max_{av}	18.7	20.1	22.7	25.9	24.3	23.2	22.5		23.1		

Table 1 (continued)

Trial sites/details	Monthly Atm. Temp. (°C)						Ave. Atm. Temp. (°C)	No. of days with supra-optimal Atm. Temp	Soil Temp. (°C)	Total rainfall (mm)	
	Oct	Nov	Dec	Jan	Feb	Mar				Seasonal (2018/19)	Historical Ave. (1981–2010)
$Hist_{av}$	18.6	20.4	22.7	23.9	23.5	22.1	22.5				
Min_{av}	5.2	9.4	12.6	13.8	11.2	11.4	10.6		17.0		
$Hist_{av}$	8.5	10.2	12.8	13.7	13.9	12.2	12.6				
No. of days > 25 °C	0	1	8	19	12	9		49			
No. of days > 30 °C	0	0	0	4	4	0		8			
Hastings (under mesh cover)											
$Season_{av}$	13.6	16.2	19.0	21.2	19.3	18.6	18.9		19.0		
$Hist_{av}$	13.6	15.3	17.7	18.8	18.7	17.1	17.5				
Max_{av}	19.7	20.9	22.4	28.2	26.6	22.6	24.1		22.8		
$Hist_{av}$	18.6	20.4	22.7	23.9	23.5	22.1	22.5				
Min_{av}	7.5	11.4	14.2	15.8	13.6	13.4	13.7		15.5		
$Hist_{av}$	8.5	10.2	12.8	13.7	13.9	12.2	12.6				
No. of days > 25 °C	1	2	9	27	19	3		61			
No. of days > 30 °C	0	0	1	10	10	0		21			

All historical averages were based on a 30-year period (1981–2010)

$Season_{av}$ seasonal average, Max_{av} maximum average, Min_{av} minimum average, $Hist_{av}$ historical average

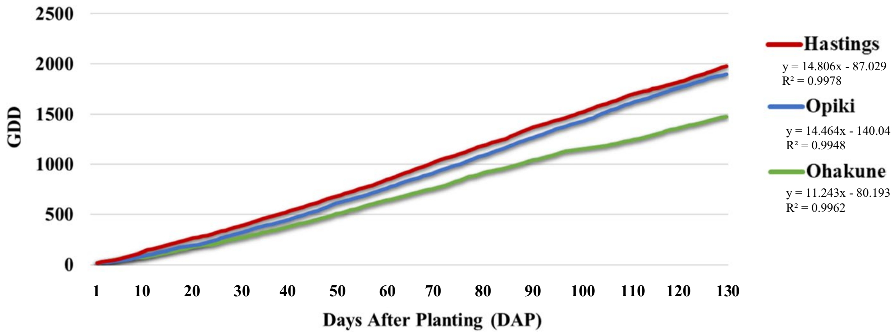

Fig. 1 Accumulated growing degree days (GDD) in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season at 4.4 °C base temperature

Abiotic Stress Effects on Morpho-physiological Characteristics of Potato Crops

Weather extremes in the 2018/19 season accompanied by drought and heat stress affected the morpho-physiology of the potato crops. The influence of the environment (trial sites) was significant on plant height ($p < 0.001$), stem diameter ($p < 0.001$), total plant leaf area ($p < 0.01$), net photosynthesis (P_N) ($p < 0.05$), transpiration rate (E) ($p < 0.001$), stomatal conductance (g_s) ($p < 0.001$), and chlorophyll content (ChlC) ($p < 0.01$) (Fig. 2, Supplementary Table 1). The influence of cultivars was also significant for plant height (p < 0.001), stem diameter ($p < 0.001$), total plant leaf area ($p < 0.01$), and ChlC ($p < 0.01$) but not significant for P_N, E, and g_s (Fig. 3, Supplementary Table 1).

Relative to Ohakune, plant height and total plant leaf area were higher in Hastings by 43% (112.1 cm) and by 59% (6892 cm^2), respectively, but the stem diameter was lower by 13% (13.9 mm). In contrast, plant height and total plant leaf area were lower in Opiki by 4% (75.2 cm) and by 66% (1489 cm^2), respectively, but higher stem diameter by 6% (16.9 mm) relative to Ohakune. Amongst the cultivars, 'Fianna' had the most vigour in terms of plant height (100.5 mm) and stem diameter

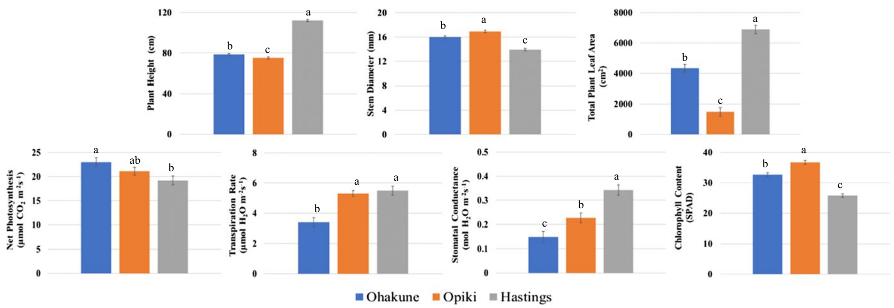

Fig. 2 Morpho-physiological parameters of commercial potato cultivars as affected by environments in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season at 65 DAP (days after planting). Means ± standard error is presented and letters indicate significant differences calculated on Tukey's HSD test ($p \leq 0.05$)

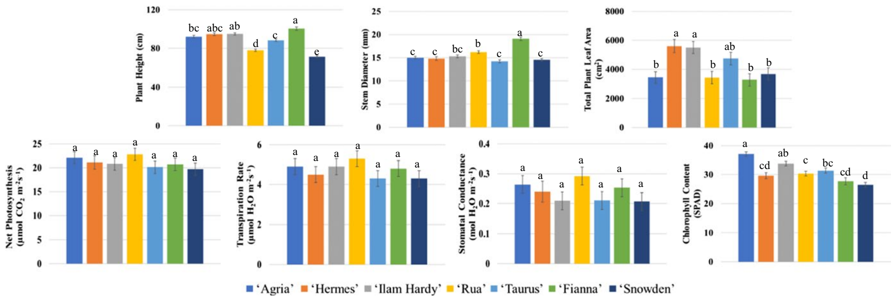

Fig. 3 Morpho-physiological parameters of commercial potato cultivars as affected by cultivars in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season at 65 DAP (days after planting). Means ± standard error is presented and letters indicate significant differences calculated on Tukey's HSD test ($p \leq 0.05$)

(19.1 mm). On the other hand, 'Hermes' had the highest total plant leaf area (5605 cm^2) but was not significantly different from 'Ilam Hardy' (5506 cm^2).

On physiological parameters, P_N was lower by 16.5% (19.2 µmol $CO_2 m^{-2} s^{-1}$) in Hastings but was not significantly different from Opiki (21.0 µmol CO_2 m^{-2} s^{-1}), and Opiki compared with Ohakune (23.0 µmol CO_2 m^{-2} s^{-1}). The E was higher by 61.8% (5.5 mmol H_2O m^{-2} s^{-1}) in Hastings and by 55.9% (5.3 mmol H_2O m^{-2} s^{-1}) in Opiki, compared to Ohakune. Correspondingly, g_s was higher by 129.5% (0.342 mol H_2O m^{-2} s^{-1}) in Hastings and by 52.3% (0.227 mol H_2O m^{-2} s^{-1}) in Opiki relative to that in Ohakune. ChlC was reduced by 22.4% (25.8 SPAD) in Hastings, whilst increased by 12.2% (36.7 SPAD) in Opiki. On cultivar effects, 'Agria' had the highest ChlC (37.1), followed by 'Ilam Hardy' (33.8) and 'Taurus' (33.8).

Abiotic Stress Effects on Final Yield and Tuber Quality of Potato Crops

The influence of the environment (trial sites) was very highly significant ($p < 0.001$) for total yield (TY), marketable tuber yield (MY), dry matter content (DMC), harvest index (HI), and specific gravity (SG); highly significant for percent yield loss (YL); and significant ($p < 0.05$) for the number of tubers plant^{-1} (NTP) and number of marketable tubers plant^{-1} (NMTP) (Fig. 4, Supplementary Table 2). In the same way, the influence of cultivar was very highly significant ($p < 0.001$) for all parameters, except for the YL and NTP, which is highly significant ($p < 0.01$) (Fig. 5, Supplementary Table 2).

Ohakune had the highest TY (72.4 t ha^{-1}), MY (57.8 t ha^{-1}), NTP (24.7), NMTP (10.7), DMC (19.8%), HI (70.9%), and SG (1.078). On the other hand, Opiki had lower TY (41.0 t ha^{-1}) and MY (34.8 t ha^{-1}) but was not significantly different from Hastings' TY (41.9 t ha^{-1}) and MY (31.7 t ha^{-1}). Hastings had the most YL (24%), followed by Ohakune (20%) and Opiki (15%). Opiki had 35.6% less NTP (15.9) and 14.9% NMTP (9.3), whilst Hastings had 18.6% less NTP (20.1) and 6.5% NMTP (10.0). In the same way, Opiki and Hastings had significantly lower DMC (16.7%, 18.5%), HI (66.5%, 62.6%), and SG (1.069, 1.071), respectively, compared to Ohakune.

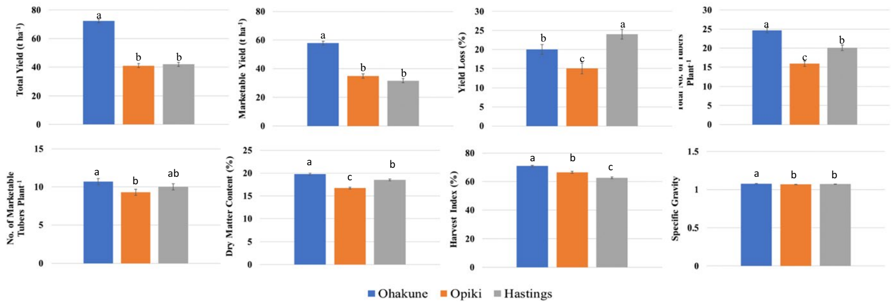

Fig. 4 Yield and tuber quality parameters of commercial potato cultivars as affected by environments in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season at 130 DAP (days after planting). Means ± standard error is presented and letters indicate significant differences calculated on Tukey's HSD test ($p \leq 0.05$)

Amongst the cultivars 'Rua' had the least TY (37.9 t ha^{-1}), whilst 'Hermes' (56.2 t ha^{-1}) had the highest TY, which was not significantly different from 'Taurus' (56.0 t ha^{-1}), 'Ilam Hardy' (53.6 t ha^{-1}), 'Agria' (53.3 t ha^{-1}), 'Fianna' (53.1 t ha^{-1}), and 'Snowden' (51.9 t ha^{-1}). 'Taurus' had the highest MY (49.1 t ha^{-1}) but was not significantly different from 'Snowden' (47.5 t ha^{-1}), which also had the least YL (8.5%). The reference cultivar, 'Agria', had relatively low MY (37.9 t ha^{-1}) and was amongst the cultivars with high YL (28.9%). 'Hermes' had the greatest NTP (27.3) but was not significantly different from 'Ilam Hardy' (24.0), and 'Ilam Hardy' from 'Taurus' (23.4). 'Hermes' also had the greatest NMTP (14.4), which was not significantly different from 'Taurus' (13.2) and 'Snowden' (12.3), whilst 'Agria' had the least NMTP (5.9).

On the other hand, 'Snowden' had the highest DMC (20.4%) but was not significantly different from 'Hermes' (19.9%), whilst 'Ilam Hardy' had the lowest (16.5%). 'Snowden' also had the highest SG (76.3%) but was not significantly different from 'Taurus' (75.4%), whilst 'Agria' had the lowest (61.9%). On the other hand, 'Hermes' and 'Snowden' had the highest SG (1.080), but it was not significantly different from 'Taurus' (1.077).

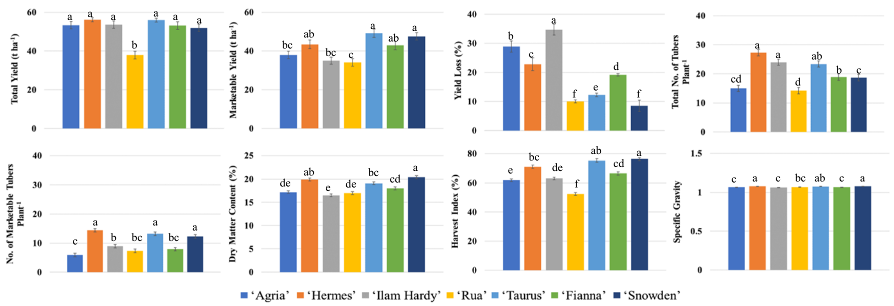

Fig. 5 Yield and tuber quality parameters of commercial potato cultivars as affected by cultivars in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season at 130 DAP (days after planting). Means ± standard error is presented and letters indicate significant differences calculated on Tukey's HSD test ($p \leq 0.05$)

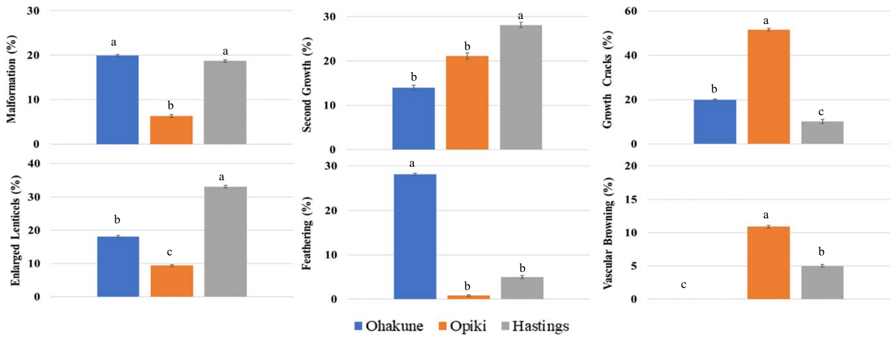

Fig. 6 Tuber physiological disorders of commercial potato cultivars as affected by environments in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season at 130 DAP (days after planting). Means ± standard error is presented and letters indicate significant differences calculated on Tukey's HSD test ($p \leq 0.05$)

Abiotic Stress Effects on Tuber Physiological Disorders of Potato Crops

The influence of the environment (trial sites) was very highly significant ($p < 0.001$) on the formation of tuber physiological disorders such as malformation, growth cracks, enlarged lenticels, feathering, and vascular browning, and highly significant ($p < 0.01$) for second growth (Fig. 6, Supplementary Table 3). In the same way, the influence of cultivars was also very highly significant ($p < 0.001$) for all parameters but not significant for vascular browning (Fig. 7, Supplementary Table 3).

Feathering (28.1%), malformation (19.1%), and growth cracks (19.1%) in Ohakune; growth cracks (51.6%) and second growth (21.1%) in Opiki; and enlarged lenticels (33.1%) and second-growth (28.1%) in Hastings were the most common tuber physiological disorders observed (Fig. 8). Vascular browning was observed in Opiki and Hastings, whereas hollow heart though in a small number of tubers only was recorded in Hastings.

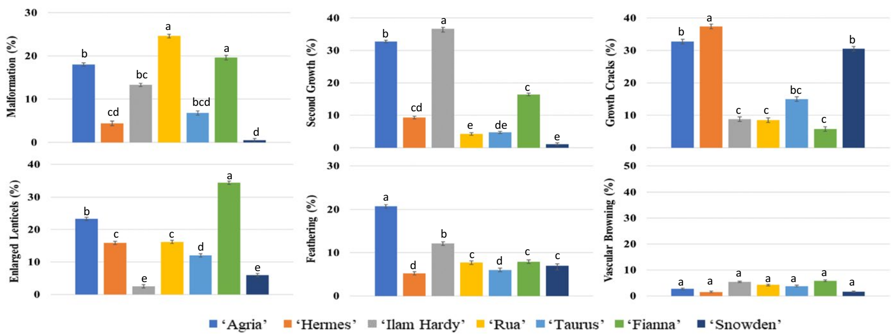

Fig. 7 Tuber physiological disorders of commercial potato cultivars as affected by cultivars in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season at 130 DAP (days after planting). Means ± standard error is presented and letters indicate significant differences calculated on Tukey's HSD test ($p \leq 0.05$)

Fig. 8 Tuber physiological disorders at final harvest (130 days after planting): in Ohakune, **a** feathering in 'Agria', **b** tuber cracking (superficial cracks) in 'Hermes', **c** second-growth (secondary tubers), and **d** tuber malformation in 'Ilam Hardy'; in Opiki, **e** secondary tubers and **f** vascular browning in 'Ilam Hardy', **g** second-growth (heat sprouts) in 'Agria', **h** superficial cracks in 'Hermes', **i** second-growth (chain tubers) in 'Ilam Hardy'; in Hastings **j** heat sprouts in 'Ilam Hardy', **k** enlarged lenticels in 'Hermes', **l** chain tubers in 'Fianna', **m** secondary tubers and **n** hollow heart in 'Agria', and **o** heat sprouts in 'Hermes'

'Agria', 'Rua', 'Fianna', and 'Ilam Hardy' were more susceptible to tuber malformations. On the other hand, 'Hermes' and 'Snowden' were more susceptible to growth cracks, whilst 'Taurus' was less susceptible to growth cracks. 'Ilam Hardy' appeared to be susceptible to second growth i.e., heat sprouts and secondary tubers. Additionally, the following is the order of tolerance of the different cultivars to physiological disorders: 'Taurus' > 'Snowden' > 'Hermes' > 'Fianna' > Rua' > 'Ilam Hardy' > 'Agria', during the 2018/19 season.

Genotype × Environment Interaction Under the Multi-environment Trial of Potato Crops

The individual effects of genotype (G) and environment (E), and genotype × environment (G × E) interaction were very highly significant ($p < 0.001$) for marketable tuber yield based on ANOVA (Table 2). Further, the ANOVA of average marketable tuber yields across the seven cultivars and the three environments showed that 77.2% of the total SS (sum of squares) was attributed to environmental effects, 13.8% to genotypic effects, and 9.0% to G × E interaction.

Moreover, the following is the order of the attained average marketable tuber yield of potato cultivars: 'Taurus' > 'Snowden' > 'Hermes' > 'Fianna' > 'Agria' > 'Ilam Hardy' > 'Rua', based on the generated biplot (Fig. 9). The average marketable tuber yields of 'Taurus' (49.1 t ha^{-1}) and 'Snowden' (47.5 t ha^{-1}) were well-above the mean (41.4 t ha^{-1}) (intersect in the biplot); 'Hermes' (43.4 t ha^{-1}) and 'Fianna' (42.9 t ha^{-1}) were close to the mean, whilst 'Agria' (37.9 t ha^{-1}), 'Ilam Hardy' (35.0 t ha^{-1}), and 'Rua' (34.1 t ha^{-1}) were below the mean.

Discussion

Weather Data

The 2018/19 season had distinct variations and extreme weather patterns with Opiki and Hastings more negatively affected than Ohakune. It was the third hottest summer on record, after 2017/18 and 1934/35 (NIWA 2020). The national average temperature reached 17.9 °C, which is 1.2 °C above the 1981–2010 average (NIWA 2020). The abnormally high temperature was due to marine heatwaves around New Zealand coastlines, especially in the Hawke's Bay region (Salinger et al. 2020). The supra-optimal average atmospheric temperature (AT) (> 25 °C) in Opiki and Hastings for extended periods confirmed the presence of heat stress amongst the potato crops. Moreover, mesh coverings in Hastings aggravated this condition by creating

Table 2 Analysis of variance for the genotype × environment interaction for average marketable tuber yield of seven commercial potato cultivars in the Ohakune, Opiki, and Hastings trial sites during the 2018/19 potato growing season

	df	Sum Sq	Mean Sq	*F* value	Pr(> *F*)	
Environment (Env)	2	91,166	45,583	59.0470	6.692e-06	***
Rep Env	9	6948	772	2.9399	0.0021451	**
Genotype (Gen)	6	16,242	2707	10.3090	1.165e-10	***
Env × Gen	12	10,608	884	3.3666	0.0001043	***
Residuals	419	110,022	263			

Significance codes: ***, $P < 0.001$; ** $P < 0.01$

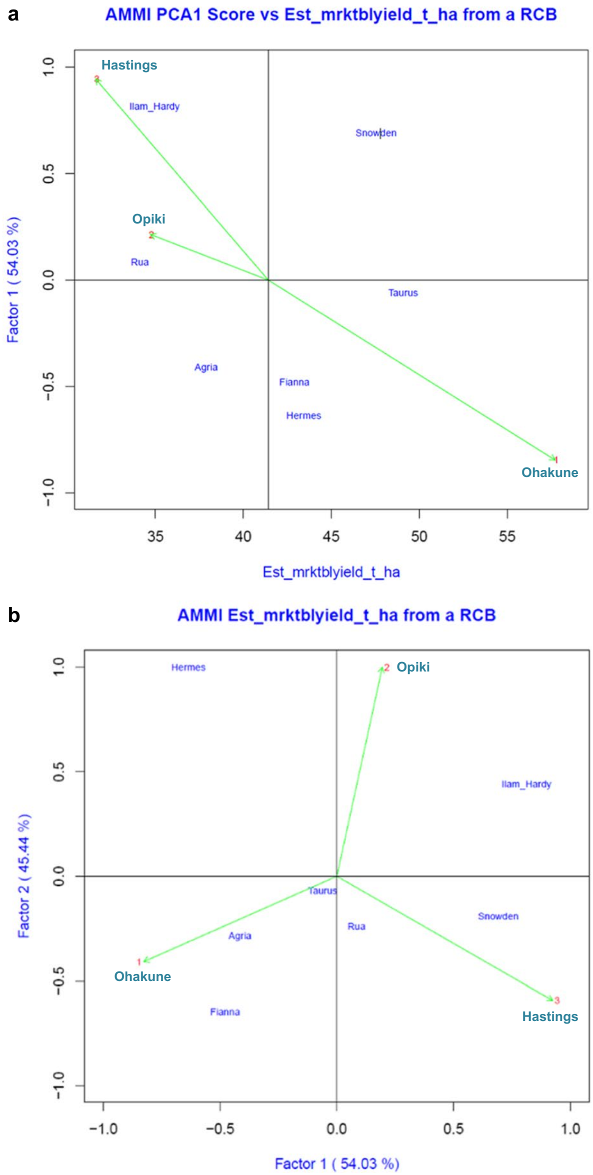

Fig. 9 Additive Main Effect and Multiplicative Interaction (AMMI1) biplot showing the **a** Interaction Principal Component Analysis (IPCA1) (Factor1) vs. estimated average marketable tuber yield and **b** AMMI2 biplot showing the first two principal axes of interaction (IPCA2 vs. IPCA1) of seven commercial potato cultivars evaluated in three environments in the North Island of New Zealand during the 2018/19 growing season

a microclimate raising the temperature by 2 °C. In an earlier study, a 1 °C increase was observed under mesh-covered potato crops (Merfield et al. 2015). However, this was conducted on the South Island, where the AT is much lower than on the North Island. Soil temperature (ST) had the same trend as AT in all sites. Though, irrigation in Ohakune and Hastings could have had a cooling effect on ST, whilst the sub-optimal rainfall and non-irrigated Opiki could have aggravated the increase in ST.

Total rainfall in all sites was below the optimum range (500–700 mm) for potato production. Rainfall was recorded below normal in the northern and western parts of the North Island, including the Manawatu–Wanganui region (NIWA 2020). Across sites, particularly low rainfall was experienced in mid-spring (October) which was 40–80% lower than the historical average. This coincided with crop emergence and stolon initiation in Opiki. By early summer (December), heavy downpours occurred in Opiki and Hastings, caused by a storm and a wet December, respectively (NIWA 2020). However, this was followed by a generally drier mid-summer (January) that coincided with tuber bulking, up to early autumn (March). This resulted in a rapid decrease in soil moisture levels and progressed to severely dry soils in the northern and western regions of the North Island (NIWA 2020).

Abiotic Stress Effects on Morpho-physiological Characteristics of Potato Crops

Weather extremes accompanied by heat and drought stress in the 2018/19 season have affected the morpho-physiology of the potato crops with Opiki and Hastings more negatively impacted than Ohakune. This was aggravated by mesh covering in Hastings that increased the plant height (but reduced stem diameter) and leaf area. This can be attributed to the relatively rapid vegetative growth and the increase in the number of smaller but more leaves under high temperatures (Gawronska et al. 1992; Hastilestari et al. 2018; Lafta and Lorenzen 1995; Rykaczewska 2015; Tang et al. 2018).

In contrast, the drier conditions in Opiki reduced the plant height (but increased stem diameter), and leaf area. Drought stress can reduce the maximum leaf area index of potatoes by 29% in the field and by 63% in the greenhouse (Lahlou et al. 2003). Either or both the lowered leaf water potential that acts as a hydraulic signal and the hormonal signals (abscisic acid) produced in the root tips of potato crops may reduce leaf area expansion under drought conditions (Shahnazari et al. 2007), whereas the increase in stem diameter is a typical drought stress response where the accumulation of assimilates and conserving water into the stem are enhanced (Ohashi et al. 2008).

On the other hand, the reduced P_N in Hastings could be caused by heat stress that impaired the crop's photosynthetic activity and increased the E and g_s (Hammes and De Jager 1990; Hastilestari et al. 2018; Reynolds et al. 1990; Wolf et al. 1990). It was suggested that for every 5 °C increase above the optimum (20.0 °C) in leaf temperature of potatoes, the photosynthetic performance is reduced by 20% (Burton 1981). The increased g_s at high temperatures may improve photosynthesis either through increasing CO_2 transport to the leaves or through the cooling effect on the leaves due to higher E (Wolf et al. 1990). However, if temperatures surpass a certain threshold, it may impair photosynthesis and reduce water use efficiency (Guoju et al. 2013). On the other hand, photosynthesis is hampered by the closure of stomata to slow down the transpiration rate under drought stress, which prevents the entry of CO_2 into the leaves (Li et al. 2017) which may reduce growth rate and final yield. Meanwhile, the levels of photosynthetic pigments including chlorophylls a and b and carotenoids were reduced by up to 20% under heat stress (Hancock et al. 2014). In contrast, the increase in the ChlC under drought stress in Opiki could be due to the loss in leaf turgor pressure or a reduction in leaf growth (Ramírez et al. 2014).

Abiotic Stress Effects on Final Yield and Tuber Quality of Potato Crops

Ohakune had the highest TY, MY, NTP, HI, and SG, having temperatures close to optimum levels for potato growth and development, whilst the reduced rainfall was compensated by irrigation. In contrast, Hastings and Opiki had lower MYand tuber quality due to the presence of heat and drought stress. It is striking that the TY and MY in both sites were way below the national average of 51 t ha^{-1} (Potatoes New Zealand 2022). Heat stress alone impairs water use efficiency (Guoju et al. 2013), photosynthesis, and photosynthate production and enhances dry matter partitioning to the haulm, thereby promoting vegetative growth over tuber development (Gawronska et al. 1992; Ghosh et al. 2000; Hancock et al. 2014; Hastilestari et al. 2018). As a consequence, the tuber fresh weight, dry weight, dry matter, and HI decreased (Ghosh et al. 2000; Hancock et al. 2014; Hastilestari et al. 2018). Heat stress at the early stage of potato crop growth can completely inhibit tuber initiation (Ghosh et al. 2000; Levy et al. 1991) and reduce the dry matter partitioning to the tubers, whilst at the latter stage, reducing SG (Ghosh et al. 2000), an important quality parameter for processing-type potatoes. On the other hand, drought stress at the early stage could reduce plant height (Shock et al. 1992), delay canopy growth (Aliche et al. 2018; Jefferies 1993; Martin et al. 1992), and decrease leaf area index (Lahlou et al. 2003); arrest stolon differentiation and tuber formation (Aliche et al. 2020); and at the latter stage, hasten crop maturity (Robins and Domingo 1956) and haulm senescence (van Loon 1981).

The high MY observed for 'Hermes', 'Taurus', and 'Snowden' can be attributed to their vigorous plant growth e.g., greater leaf area that could enhance sunlight interception, higher DMC, NTP, and NMTP and lower non-marketable tubers compared to most tested cultivars. 'Rua' had the lowest TY and MY that agree with the recorded yield of the cultivar (McLeod 1973; Anderson et al. 1997). 'Ilam Hardy', on the other hand, had a relatively high TY but also had the highest YL. A common observation amongst varieties with higher MY, such as 'Hermes' and 'Taurus', is their inherent characteristics of producing a high NTP.

HI and SG were reduced in Hastings and Opiki due to the elevated temperatures that resulted in a shift in biomass distribution away from the tubers and toward the aboveground parts (Hancock et al. 2014). High SG seemed to be a common characteristic of cultivars with relatively smaller tubers such as 'Hermes' (Amjad et al. 2016) and 'Snowden' (Baritelle and Hyde 2003; Canadian Food Inspection Agency 2020; Potato Association of America 2020). In contrast, SG seems to be lower amongst cultivars with larger tubers, such as 'Agria', 'Fianna', and 'Ilam Hardy'.

Abiotic Stress Effects on Tuber Physiological Disorders of Potato Crops

The literature strongly suggests that many tuber physiological disorders are influenced by unfavourable environmental factors, including extreme atmospheric and soil temperatures, rainfall, and humidity (Hiller et al. 1985; Lugt et al. 1964; Rykaczewska 2015, 2017). In this study, the development of a specific tuber physiological disorder depended on the environment and the specific or combination of abiotic stress present during the growing season. In the cooler environment of Ohakune, feathering, a common characteristic of immature tubers having thin skin that can easily be torn at harvest and during handling (Hillerm and Thornton 2008) was the most common physiological disorder. Feathering could be due to the slower GDD accumulation throughout the growing season in Ohakune, as compared with Opiki and Hastings.

In Opiki, the arid spring followed by a very wet early summer may have encouraged growth crack formation. Whereas the moisture stress combined with supra-optimal AT and ST may have caused the premature breaking of tuber dormancy, which encouraged second-growth formation, i.e., heat sprouts, chain tubers, and secondary tuber formation. A past study suggested that this could be an indirect effect of incomplete canopy coverage due to drought stress and high temperature (Shock et al. 1992). The common practice of ground storing in New Zealand could expose the ground stored-tubers to high ST which may enhance physiological disorders.

The very highly significant influence of cultivars on the incidence of physiological disorders is indicative of strong differential susceptibility or tolerance to abiotic stress. Moreover, cultivars with naturally large and elongated tubers such as ‘Agria’, ‘Rua’, ‘Fianna’, and ‘Ilam Hardy’ were more susceptible to malformation. In contrast, cultivars that have medium-sized circular tubers such as ‘Hermes’ and ‘Snowden’ were less susceptible to malformation but more susceptible to growth cracks. The rough and slightly netted skin characteristics of ‘Hermes’ and ‘Snowden’, appeared to be enhanced by abiotic stress, which developed into growth cracks. ‘Taurus’, on the other hand, with relatively smooth skin was less susceptible to growth crack formation. The reference cultivar ‘Agria’ was also susceptible to growth cracks and second growth.

This study validates the preliminary findings in the 2017/18 season (Siano et al. 2018) where heat and moisture stresses were determined as likely causes of an array of tuber physiological disorders, which resulted in a reduction in marketable tuber yield.

Genotype × Environment Interaction Under Multi-environment Trial of Potato Crops

The environments (trial sites) were diverse causing most of the variation in the average marketable tuber yield (MY). This can be indicated by the environment’s large sum of squares. Similarly, the very significant effect of the G×E interaction also showed that the genotypes (cultivars) had differential performance in the environments.

According to Silveira et al. 2013, stable genotypes have lower influence on the G×E interaction and can be indicated by a lower IPCA1 value. In this MET, the cultivar ‘Taurus’ could be highlighted and identified as an ideal genotype because it had the highest average MY and stability (wide adaptation) compared with the reference cultivar ‘Agria’ and the other tested cultivars. In contrast, ‘Ilam Hardy’ was identified as an undesirable genotype owing to its low productivity and low stability (IPCA1 values farthest from zero) (Gauch and Zobel 1988; Kempton 1984).

On the other hand, 'Agria' showed intermediate stability only and an MY below the overall average. 'Ilam Hardy', 'Snowden', 'Hermes', and 'Fianna' were the most unstable cultivars. The unstable cultivars meant that they perform well under specific environmental conditions only (specific adaptation). Genotypes and environments located close to each other in the biplot have positive relations; thus, these enable the creation of a group of genotypes within an agronomic zone. For example, the cultivar 'Hermes' performed better in Opiki, whilst 'Snowden' in Hastings and 'Fianna' in Ohakune.

All the environments had some cultivars with MY above the overall average; but only Ohakune had all cultivars above the overall average, indicating that this was the most favourable environment to obtain high yield. The possible reason for the high marketable tuber yields is the weaker presence of abiotic stress, the application of supplemental irrigation, and relatively higher natural fertility and favourable soil properties.

Conclusions

The multi-environment trial (MET) established that in the 2018/19 season, abiotic stresses associated with climate change i.e., heat and drought stress, were present and affected the morpho-physiology, yield, and tuber quality of commercial potato cultivars. Moreover, the cultivars exhibited differential susceptibility to abiotic stresses. Heat stress increases the plant height (but reduces stem diameter), leaf area, E, and g_S, whilst drought stress suppresses plant height (but increases stem diameter), leaf area, and g_S leading to a decrease in P_N. Heat stress alone or in combination with drought stress reduces the TY, MY, NTP, DMC, and HI.

The findings confirmed that abiotic stress increases the incidence of tuber physiological disorders, resulting in reduced MY. The occurrence of a specific physiological disorder depends on the environment and the type and timing of abiotic stress present during the growing season. Cultivars that have naturally large and elongated tubers are more susceptible to tuber malformation. In contrast, cultivars that have medium-sized circular tubers are less susceptible to tuber malformation but more susceptible to growth cracks.

The G×E analysis showed location-specific adaptations (agronomic zoning) amongst the tested commercial potato cultivars. The cultivar 'Hermes' is tolerant to a combination of heat and drought stress, whilst 'Snowden' is tolerant to heat stress. 'Taurus', on the other hand, is the most stable and adaptable cultivar across the environments.

Cultural practices that are unique in New Zealand potato production systems, such as the use of mesh covering as a physical barrier to protect crops from the tomato-potato psyllid, aggravate the increase in summer temperatures. Also, the practice of ground storing could expose the ground-stored potato tubers to abiotic stresses (e.g., heat and drought stress), which dramatically affect the marketable yield and tuber quality. Moreover, rainfed farming could be less feasible in the coming years with the changing rainfall patterns and frequent incidences of drought. Besides the application of appropriate cultural management (e.g., irrigation at critical stages, planting, and harvesting timing), identifying the right commercial potato cultivars with tolerance to abiotic stress (e.g., heat and drought stress) that would perform well either in a wide array of environments (wide adaptations) or specific locations (specific adaptations) should be conducted to ensure productivity and increase the resilience of the New Zealand potato industry to climate change.

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Data Availability Data of agronomic, morpho-physiological, yield, and tuber quality of potato are included in this manuscript.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication All authors give consent for publication.

Conflict of Interest The authors declare no competing interests.

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