

Evaluating the Effect of External Conditions on the Quality Attributes of Potatoes

C. Muller^{1,*}, B. Pretorius¹, H. C. Schönfeldt¹

¹ Department Animal Science, University of Pretoria, Pretoria, South Africa

*Correspondence to C. Muller. Email: carmen.muller@up.ac.za

Abstract

The rapidly growing global population emphasises the need for high-yielding, sustainable, yet nutritious food crops, which produce consistent yields under varying agricultural conditions. There are various critical research hypotheses that propose solutions for this scenario with some of the main focus areas being crop management and precision farming practices. Even though these practices are mainly focused on improving economic output, the further downstream effect is increased food security. The objective of this study was to determine the effect of genotype-environment interactions to identify possible regions where specific cultivars are better suited than others. Internal quality and external variable data gathering for this study stretched over 3 years (2016–2018) throughout South Africa on ten different plots. The Additive Main Effects and Multiplicative Interaction (AMMI) model was used to determine the reaction of cultivars/lines in each environment and display the stability of these genotypes in the different environments. The AMMI model showed that certain cultivars are more stable in varying geographical areas, i.e. they delivered consistent results irrespective of the external factors that they were exposed to. It was found that genotypes and environments that fell closer to the 0 mark on the X-axis and were therefore more stable were less likely to be influenced by external variables.

Keywords: Agriculture; Classification; Quality; Starch

Introduction

The changing agricultural landscape, together with shifting consumption patterns associated with an increase in diseases of lifestyle epidemics, has led to the need for changes in food production systems. These changes need to not only deliver sufficient energy, but also provide nutrients to sustain human health while taking sustainable outcomes into consideration. This is all in an attempt to sustain the rapidly growing global population emphasising high-yielding, sustainable, yet nutritious food crops that produce consistent yields under varying agricultural conditions (WHO 2018). Various critical research hypotheses have been proposed for this scenario. Some of the main themes which are being investigated are to improve crop management and precision farming practices (Tein 2009). However, these fairly ambitious plans are influenced by temporal variation, a lack of region-specific focus and a lack of environmental auditing knowledge. Many countries are implementing general typology plans as developed internationally, especially in lower income areas, without considering country- and even region-specific variables. Even though

these generic plans do address and in some instances solve the negative issues, region-specific scientific data is required to further improve and sustain these solutions (McBratney et al. 2005).

Precision agriculture and region-specific agriculture are classified as modern farming practices that aim at improving production efficiency and rely on the mantra “what gets measured, gets managed”. Precision agriculture entails observing, measuring and subsequently responding to inter- and intra-field variations observed in crops. Even though these practices are mainly focused on improving economic output of farming practices, the additional downstream effect is increased food security (Walter, et al. 2017). Precision agriculture is also linked to achieving Goal 12—“responsible production and consumption”—of the Sustainable Development Goals (SDGs) as adopted by the United Nations on September 25, 2015. These 17 goals aim to end poverty, protect the planet and ensure prosperity for all by 2030 (UNDP 2019).

Responsible production entails input use efficiency in agriculture by means of region-specific agriculture to promote crops and cultivars that are ideally suited to specific environments and to achieve optimum yields and nutritional outputs (United Nations 2018) with an added benefit of consumer acceptance. The effect the climate change will have on future crops also needs to be considered especially taking rising temperatures into consideration (Raymundo, et al. 2018). Potato crop yields per unit area have shown noteworthy increases over the last 20 years in South Africa. In 1990, 130 million 10-kg bags were produced on 63.000 ha, whereas in 2018, this figure rose to 240 million 10-kg bags, which were produced on 52.000 ha (Potatoes South Africa 2019). Inappropriate crop management practices are, however, still common, leading to a decrease in possible yields, as well as having detrimental effects on the environment (Steyn 2016). With the threat of a rapidly growing population, optimisation of input use efficiency and yields is essential. The unpredictability of the agricultural sector, as well as the occurrence of unforeseen weather events, can have dramatic impacts on internal quality attributes of crops.

South Africa has a diverse potato producing landscape with tubers being cultivated in 16 different production regions spread all over the country (Franke and Sekoboane 2021). The unique South Africa landscape lends itself to production of potatoes running seamlessly throughout the winter and summer in different regions. Furthermore, due to rain-fed agriculture in some of the regions, potatoes are cultivated on dry land, while irrigation is necessary in other regions.

Potato production regions are spread over vastly differing climatic regions (Franke et al. 2013). These regions vary from Mediterranean climate in the south-western corner of the country to temperate areas to the interior plateau and subtropical climate in the northeast with a small part classified as desert in the northwest of the country (Steyn 2016). These varying climatic conditions solicit area-specific agricultural practices.

Potatoes are a widely consumed international crop that plays a cardinal role in numerous countries food baskets. Therefore, evaluating and understanding the effect that climate change will have on the crop and the way in which it is produced are essential for future food security (Raymundo et al. 2018). Understanding current crop model results and genotype-environment interactions provides researcher with information on what the effect of climate change may be.

In this study, the effect that external variables have on the internal quality attributes of potatoes with different genotypes on the South African market was investigated. It is hypothesised that specific cultivars may be more ideally suited to specific agricultural practices and, therefore, also specific geographical regions with regard to increased yield and quality.

Objective

The objective of this study was to determine the effect of genotype-environment interactions to identify possible regions where specific cultivars are better suited to grow than others.

Methodology

Data gathering took place over a 3-year period (2016–2018) across South Africa from ten different plots (Table 1). Figure 1 is a map of South Africa showing the different production regions from which potatoes were sourced for this study. All the tubers were planted as part of Potatoes South Africa's workgroup project under the standardised agricultural practices (agronomic management) of the specific areas using randomised block designs (RBD).

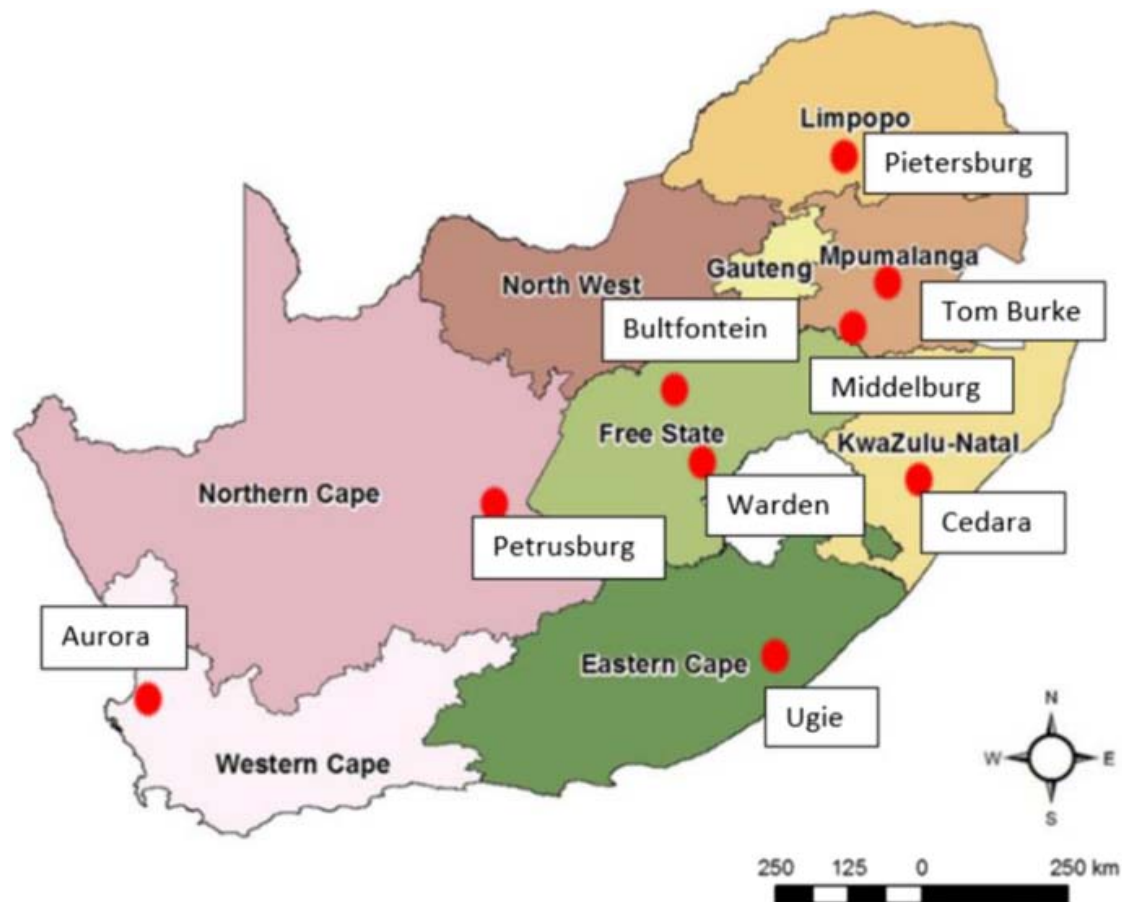


Fig. 1. Map of South African showing all the different production regions from which potatoes were sourced for this study

Table 1. Location, date of harvest, cultivars and agricultural practices (precipitation type) used

Production area	Climate classification	Plant date	Harvest date	Precipitation	Plants per ha
Bultfontein	Arid	19-Jan-16	17-Aug-16	Irrigation	25,000
Pietersburg	Arid	05-Aug-16	08-Dec-16	Irrigation	41,666
Middelburg	Temperate	11-Aug-16	01-Feb-17	Irrigation	44,444
Aurora	Arid	18-Oct-16	15-Mar-17	Irrigation	41,666
Warden	Temperate	27-Oct-16	13-May-17	Dry land	41,666
Ugie	Temperate	09-Nov-16	23-May-17	Irrigation	44,444
Tom Burke	Temperate	26-May-17	17-Oct-17	Irrigation	37,037
Pietersburg	Arid	04-Aug-17	08-Dec-17	Irrigation	41,666
Petrusburg	Arid	24-Aug-17	25-Jan-18	Irrigation	37,037
Cedara	Temperate	21-Sept-17	05-Feb-18	Irrigation	37,037
Cultivars sampled					
Sifra		Lanorma			
Mondial		Markies			
Fianna		Valor			
Taisiya					

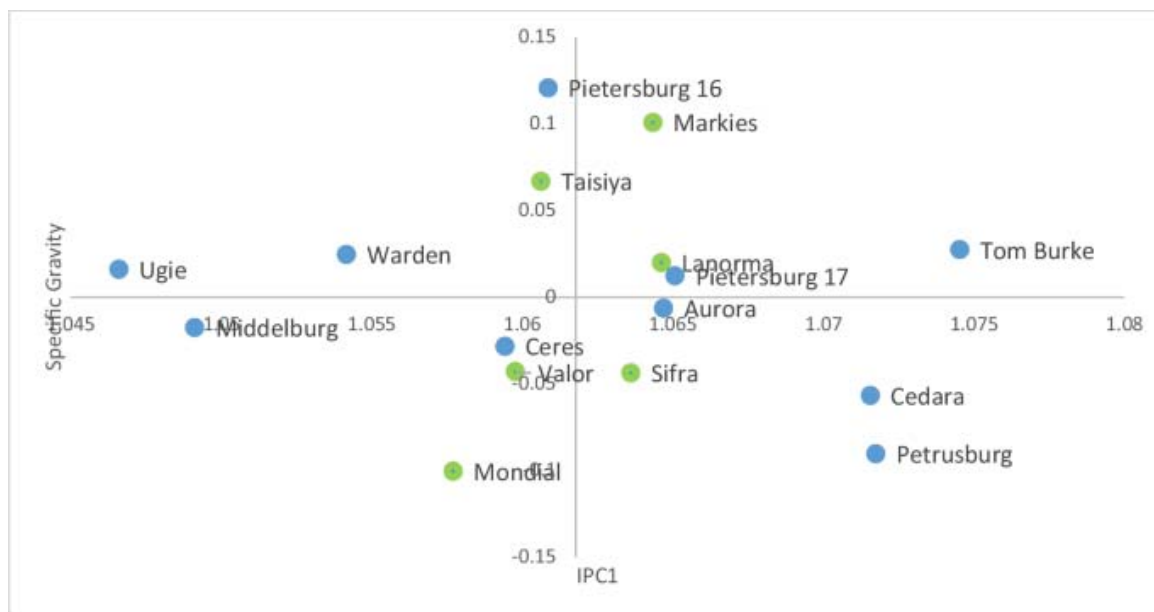


Fig. 2. AMMI for specific gravity of genotype-environment interactions

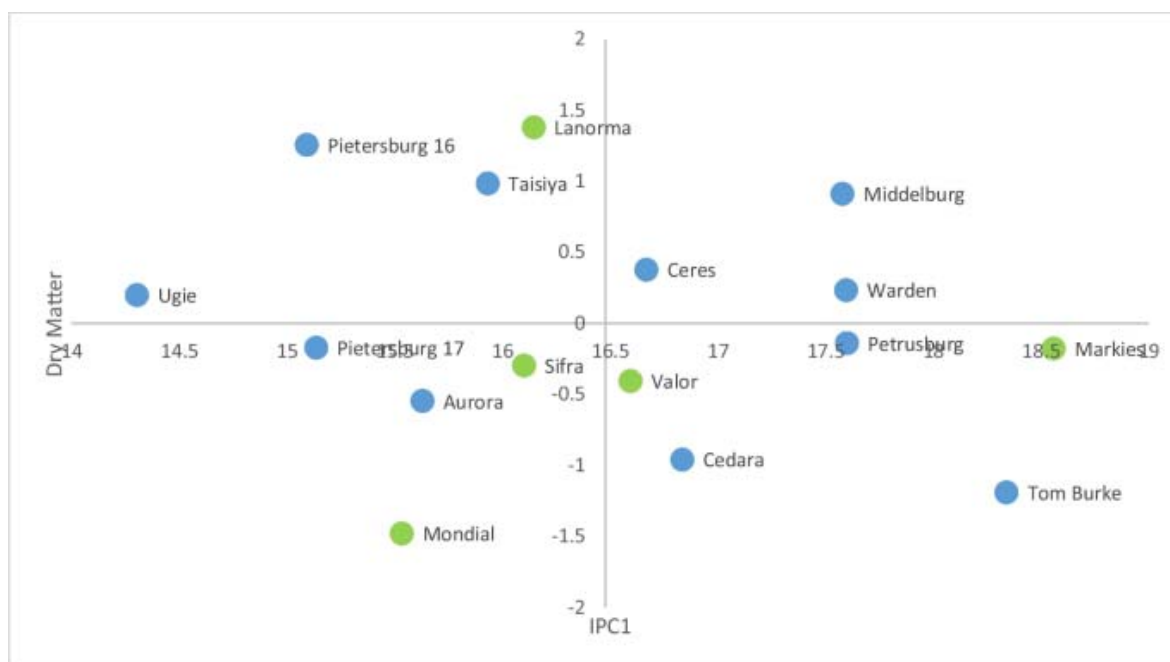


Fig. 3. AMMI for dry matter of environment genotype-interactions (not significant)

Potato Sampling Procedures

At harvest, random samples of tubers were selected and packed into 10-kg brown bags by potato trial leader and transported to the laboratory within 12 h after harvest. Table 1 is a summary of the harvest areas and agricultural practices used for the tubers from this study. Tubers were kept in the bags at 21 °C for 6 days postharvest, prior to analysis to mimic market practices. On the day of analyses, each bag per cultivar was emptied into a container,

and mixed and tubers were randomly selected for the laboratory tests. Selected tubers were thoroughly washed with distilled water and allowed to dry on paper towels.

Internal Quality Attributes

Dry Matter Analysis

Three randomly selected, fresh, “as is”, tubers from each cultivar from each production area were sent in a brown paper bag for dry matter analysis. These tubers were selected at random from the 10-kg bags as received from the farm. Dry matter was gravimetrically determined according to the AOAC (Association of Official Agricultural Chemists) 934.01 method at a SANAS (South African National Accreditation System)-accredited laboratory. Analyses were done in duplicate on the flesh and skin of each tuber.

Dry matter content was seen as a more reliable method than gravimetric determination as it is a validated analytical method of evaluation. Dry matter is measured by drying a known wet weight of finely grated tuber, placing it in a drying oven to extract all the moisture from the flesh and then weighing it again to determine the total dry matter content (AOAC 2000).

Specific Gravity Analysis

Five tubers from each cultivar from each production area were individually analysed for specific gravity. Specific gravity was determined by weighing (washed and dried) tubers (flesh and skin) individually. This was followed by an underwater weighing where the tubers were individually placed in a net and submerged in water and weighed. Specific gravity was then calculated with the following equation (Eq. 1) (DAFF 2013):

$$\text{Specific gravity} = \frac{\text{Weight in air}}{(\text{Weight in air} - \text{Weight under water})} \quad (1)$$

Chip Colour

Chip colour analyses were done at the Institute of the Agricultural Research Council, Roodeplaat, South Africa. Chipping colour analyses were done using the Hunterlab method, using the UltraScan PRO, as described by the United States Department of Agriculture (USDA 1977). The test determines compliance with a specified fry colour. The South African potato industry standard for acceptable chip colour is set at 50 and higher.

Longitudinal slices (approximately 1.3 mm in thickness) were cut from the centre portion of the potatoes. These were fried in oil at 185 °C for 100 s. A minimum of 40 slices were used for colour evaluation. Visual colour scoring was done on a scale of 1–10 of increasing dark colour with 1 denoting the lightest colour and 10 denoting the darkest colour with associated designations as shown in Table 2 (USDA 1977; Ezekiel et al. 2003).

Table 2. Hunterlab colour values corresponding to different chip colour scores (Ezekiel et al. 2003)

Chip colour score	Mean	Range
1	81.0	80-82
2	77.3	75-79
3	69.3	67-74
4	62.0	61-66
5	55.7	54-60
6	51.7	50-53
7	48.3	45-49
8	40.1	40-44
9	37.7	36-39
10	30.0	25-35

External Variables

Marketing Index

To determine the performance of the cultivars in terms of yield and quality, the yield, size distribution and class were used to calculate a marketing index at the average market prices the day of harvest. The yield, multiplied by the prevailing price determined by the size distribution and rating, gives the marketing index (Eq. 2).

$$\text{Marketing index} = \frac{\text{crop yield per hectare} \times \text{market price on day of harvest}}{100} \quad (2)$$

Weather Data

Data used for rainfall and heat unit calculation was sourced from the Agricultural Research Council Agro-Meteorology Programme for weather stations. These weather stations are situated on more than 500 plots throughout South Africa and maintain an operational national agro-climate network database, as well as a climate databank (ARC 2019). Rainfall data as received from the weather station was summed over the growing period.

Subsequently, heat units were calculated from the weather data using the set formula as described in horticulture guidelines (Eq. 3). A threshold value of 5.00 was used for potatoes (Worthington and Hutchinson 2005).

$$\text{Heat unit} = \frac{(\text{Temperature max} + \text{Temperature min})}{2} - (\text{Threshold Temperature}) \quad (3)$$

Fertiliser

Fertilisation practices and amount at the beginning, as well as throughout the planting cycle, were noted. Fertiliser application is area specific and data was obtained from each individual farmer on the amount of fertiliser that was applied during the growing period. Fertiliser is expressed as kg per hectare for nitrogen, phosphorus and potassium.

Plants and Yield per Hectare

Plants and yield per hectare were calculated using the following equations:

$$\frac{10,000\text{m}^2}{\text{sample area } \text{m}^2} = \text{Multiplying factor} \quad (4)$$

$$\frac{\text{kg yield or plants from sample area}}{1000} = \text{ton or plants per sample area} \quad (5)$$

$$\text{ton/plants per sample area (Eq.5)} \times \text{multiplying factor (Eq.4)} = \text{tons /plants per hectare} \quad (6)$$

Table 3. Sizing guide for potatoes in South Africa (DAFF 2019)

Sizing	Weight
Baby	5–50 g
Small	50–100 g
Medium	90–170 g
Large-medium	150–250 g
Large	250 g +

Cultivar Class, Size and Waste

Potato class and size were evaluated according to the guidelines supplied by the Department of Agriculture and Potatoes South Africa. Potatoes sizing is classified as shown in Table 3. Potatoes are scored in classes based on the absence of diseases and blemishes visible to the eye and the presence of quality factors as stipulated by specific end users (DAFF 2019).

Statistical Analysis

All data for the internal and external evaluations were captured on a spreadsheet. A one-way random block design (RBD) analysis using Fisher's protected least significant differences (FPLSD) *t*-test at the 5% level of significance was used to separate means among cultivars for dry matter and specific gravity (Payne et al. 2012).

The genotype-environment interaction was analysed using the AMMI model (Gauch 2013). The AMMI model is suitable for determining the reaction of cultivars/lines in an environment and displays the stability of these genotypes in different environments (Steyn et al. 1993). This model is explained by sums of additive and multiplicative terms which result from the singular value decomposition (SVD) or principal component analysis (PCA) of the interaction matrix ($p < 0.01$). The model had a two-way factorial design, with each treatment specified by a genotype and environment combination. If a cultivar or an environment has an Interaction Principal Component (IPC) score near zero, it has a small interaction; thus, it is stable in response. A cultivar or environment which lies further from zero is more sensitive to interactions and thus shows more variance (Smith and Smith 1992).

In an attempt to elucidate the variance that is observed between cultivars and over production areas, an AMMI model was constructed to investigate the genotype-environment interaction for the internal characteristics (i.e. dry matter and specific gravity). For both of these characteristics, six different cultivars, namely Markies, Valor, Lanorma, Sifra, Taisiya and Mondial (Fianna was not included in this model as there were not enough relevant samples), were selected together with ten environments, i.e. Tom Burke, Petrusburg, Warden, Middelburg, Cedara, Ceres, Aurora, Pietersburg 2016, Pietersburg 2017 and Ugie (Bultfontein was not included in the model as there were not enough relevant samples). Each interaction was tested three times.

The AMMI model was constructed using 20 variables: fertiliser (nitrogen, phosphorus, potassium), internal characteristics (dry matter, specific gravity, chip colour, sizing (baby, small, medium, large-medium, large), cultivar classes (1, 2, 3), heat units, plants per hectare, rainfall, yield in tons per hectare, marketing index, and waste.

Results and discussion

In Table 4, the specific gravity and dry matter means are compared for various cultivars over the production areas in which the different cultivars were grown and analysed at the 5% significance level. Significant differences were found for specific gravity between different cultivars in six of the ten production areas: Aurora ($p = 0.040$), Pietersburg 16 ($p < 0.001$), Petrusburg ($p = 0.008$), Cedara ($p = 0.044$) (arid), Middelburg ($p = 0.023$) and Warden ($p = 0.002$) (temperate). Significant differences were found for dry matter values between different cultivars in four of the ten regions, i.e. Aurora ($p = 0.048$), Pietersburg 16 ($p < 0.001$), Ceres ($p = 0.026$) (arid) and Middelburg ($p = 0.031$) (temperate).

Table 4. Specific gravity and dry matter analysis of seven cultivars' tubers over ten production areas by one-way random block design (RBD) analysis using Fisher's protected least significant differences (FPLSD) *t*-test at the 5% level of significance

Specific gravity								
Area	<i>p</i> -value	Cultivar						
		Sifra	Lanorma	Mondial	Markies	Fianna	Valor	Taisiya
<i>p</i> -value	<i>p</i> < 0.05	< 0.001	< 0.001	< 0.001	< 0.001	0.354	< 0.001	< 0.001
Aurora	0.040	1.061 ^{a,ii,iii}	1.063 ^{a,ii,iii,iv}	1.068 ^{ab,ii,iii}	1.071 ^{b,iv,v}	1.071 ^b		
Cedara	0.044	1.080 ^{c,iv}	1.074 ^{bc,vi}	1.069 ^{ab,iii}			1.073 ^{abc,iii}	1.064 ^{a,iii}
Ceres	0.411	1.062 ^{ii,iii}	1.061 ^{ii,iii}	1.059 ⁱⁱ	1.060 ^{ii,iii}	1.070		1.056 ⁱⁱ
Middelburg	0.023	1.050 ^{ab,i}	1.057 ^{bc,ii}	1.045 ^{a,i}	1.047 ^{ab,i}	1.064 ^c	1.049 ^{ab,i}	
Petrusburg	0.008	1.076 ^{bc,iv}	1.071 ^{ab,v,vi}	1.078 ^{c,iv}	1.065 ^{a,iii,iv}			1.066 ^{a,iii}
Pietersburg 16	< 0.001	1.056 ^{b,i,ii}	1.065 ^{c,iii,iv,v}	1.045 ^{a,i}	1.076 ^{d,v,vi}		1.055 ^{b,i,ii}	
Pietersburg 17	0.072	1.066 ⁱⁱⁱ	1.070 ^{iv,v,vi}	1.062 ^{ii,iii}			1.059 ⁱⁱ	
Tom Burke	0.057	1.076 ^{iv}		1.069 ⁱⁱⁱ	1.080 ^{vi}		1.069 ⁱⁱⁱ	
Ugie	0.053	1.051 ⁱ	1.047 ⁱ	1.040 ^j				1.047 ⁱ
Warden	0.002	1.058 ^{i,ii,iii}	1.060 ^{ii,iii}	1.042 ⁱ	1.056 ⁱⁱ		1.054 ^{i,ii}	1.055 ⁱⁱ
Dry matter (%)								
Area	<i>p</i> -value	Cultivar						
		Sifra	Lanorma	Mondial	Markies	Fianna	Valor	Taisiya
<i>p</i> -value	<i>p</i> < 0.05	< 0.001	0.007	0.001	0.286	0.230	< 0.001	0.008
Aurora	0.048	14.28 ^{a,i,ii}	15.17 ^{ab,i,ii}	16.34 ^{abc,iii}	17.47 ^{bc,i}	17.52 ^c		
Cedara	0.113	16.57 ^{iii,iv,v}	14.81 ^{i,ii}	16.97 ^{iii,iv}			18.00 ⁱⁱ	15.57 ⁱⁱ
Ceres	0.026	16.37 ^{ab,ii,iii,iv}	16.58 ^{ab,i,ii}	15.32 ^{a,ii,iii}	18.05 ^{bc,i,ii}	19.59 ^c		17.06 ^{ab,ii}
Middelburg	0.031	16.85 ^{ab,iii,iv,v}	19.20 ^{bc,iii}	16.14 ^{a,iii}	18.12 ^{abc,i,ii}	20.31 ^c	17.23 ^{ab,ii}	
Petrusburg	0.357	18.25 ^{iv,v}	17.16 ^{ii,iii}	16.40 ⁱⁱⁱ	19.62 ^{i,ii}			16.39 ⁱⁱ
Pietersburg 16	< 0.001	14.01 ^{b,i}	16.16 ^{c,i,ii}	11.98 ^{a,i}	18.29 ^{d,i,ii}		14.32 ^{b,i}	
Pietersburg 17	0.812	14.84 ^{i,ii,iii}	14.54 ^l	14.40 ^{i,ii,iii}			15.37 ⁱ	
Tom Burke	0.199	18.56 ^v		19.30 ^{iv}	21.10 ⁱⁱ		18.09 ⁱⁱ	
Ugie	0.758	13.94 ⁱ	14.34 ⁱ	13.04 ^{i,ii}				13.81 ⁱ
Warden	0.080	17.35 ^{iv,v}	17.13 ^{ii,iii}	15.42 ^{ii,ii}	20.27 ^{i,ii}		18.23 ⁱⁱ	17.18 ⁱⁱ

Superscript letters show significant differences over cultivars

Roman numerals show significant differences over production areas

Fianna was the only cultivar that showed no significant difference between the various production areas for specific gravity (1.064–1.071) and dry matter (17.52–20.31%). All the other cultivars differed significantly over the various production areas for specific gravity and dry matter. No specific conclusions could be drawn as in both instances, with dry matter and specific gravity, half of the areas where significant differences were observed were in arid areas and the other half temperate, i.e. in different climatic regions.

As specific gravity measurements are less complicated to obtain than dry matter values, this method is used more often as the chosen method of evaluation. Specific gravity is one of the most common methods used in the potato industry to determine the cooking and chipping quality of tubers. Specific gravity is a determining factor of textural properties and cooking quality (Potatoes South Africa 2019).

Oregon State University developed a specific gravity and dry matter reference guide which indicates the relationship between specific gravity and dry matter. Specific gravity values most commonly fall in ranges between 1.055 and 1.095 with correlating dry matter values of between 16.5 and 24% (Oregon State University 2010). In a study conducted in Pakistan, the specific gravity of 32 different cultivars of potatoes was found to vary between 1.0343 and 1.1443 (Abbas et al. 2011), which is a wider and higher range than the average values seen in European potatoes (1.045–1.085) (Anzaldúa-Morales et al. 1992). A more recent study in Japan showed specific gravity values ranging from 1.055 to 1.110. The minimum value of the range is higher than that seen in Europe and Pakistan together with a higher top range value (Sato et al. 2017) as reported in van Niekerk et al. (2016). In the current study, specific gravity ranged between 1.040 and 1.080 and dry matter between 13.04 and 21.10%. This can be explained by the different cultivars and respective agricultural practices that are used in different countries (Daccache et al. 2012).

As potatoes are sensitive to environmental conditions, international agricultural practices and genotypes cultivated differ, which leads to these variances seen in tuber internal quality characteristics (Hijmans 2003). A comparative study conducted in England and Wales found that soil types and water logging of soil had an impact on the crop yield and quality. It was also noted that the genotype-environment interaction has a significant influence of tuber quality and not just the agricultural practices used (Daccache et al. 2012). As shown above, specific gravity of tubers in Pakistan varies vastly, which can be due to the differing agricultural landscape and climatic regions. Soil salinity and lack of proper irrigation water in Pakistan are some of the main concerns for the potato industry and these known variables along with different climatic regions can be the cause of the vast difference seen in specific gravity values (Majeed and Muhammad 2018). Japan has four main cropping seasons, meaning it has winter and summer production necessitating cultivars that are adapted to the specific climatic conditions. As seen with South African potatoes, all of these variables can have an effect on the final product. Many of the tubers cultivated in Japan have European and American descent and were adapted to grow in specific conditions in Japan for improved yield. Similarities are seen in the specific gravity values of Japanese- and American-grown cultivars which may be due to their lineage (Deguchi et al. 2016).

It is evident that the international potato fraternity have similar end goals; however, the agricultural practices used to achieve these goals need to be adapted and tailored to country-specific conditions. Optimising potato production at a regional level ensures resource use efficiency and longevity of the production system and crop.

Starch is the main carbohydrate and also the major storage compound found in potatoes. Starch content is directly related to specific gravity and dry matter in tubers. According to Oregon State University, 60–80% of the dry matter is present as starch (Oregon State University 2010). A study conducted in South Africa in 2016 found that 67–74% of dry matter is present as starch (van Niekerk et al. 2016). Therefore, high-gravity or high-solid tubers are associated with high levels of starch.

There is a significant difference in the distribution of dry matter throughout the flesh and skin of the tuber. Peeling, slicing and handling can have an effect on the dry matter content of a tuber. With this all taken into account, dry matter is still the best way to evaluate the total quantity of solids in a tuber (Thybo et al. 2004). The higher the dry matter content, the lower the water content, which will mean that such a potato has a higher specific gravity. Potatoes with a higher dry matter and low moisture content are mealy, and ideal for baking. Potatoes with a low dry matter and high moisture content are waxy and ideal for boiling (South African Department of Environment and Primary Industries 2000).

Table 5 is a summary of all the data as captured over 3 years, ten environments/production areas and the tubers that had enough data entries for robust statistical analysis (Markies, Lanorma, Sifra, Valor and Taisiya). This table shows the minimum, maximum and mean values of all the variables that were measured. In total, 150 values were captured for each variable (Figs. 2 and 3) .

The initial data showed that there was no significant genotype-environment interaction for the internal quality attribute of dry matter ($p = 0.093$) and it will, therefore, not be discussed any further (Fig. 3). Specific gravity had a genotype-environment interaction at a 0.0000004 level of probability, making it highly significant.

Interaction Principal Component (IPC1) scores were calculated using data reported in Table 5. IPC1 scores are the scores that identified significant interaction scores. Lower IPC1 scores show a cultivar or environment that is more stable, while higher IPC1 scores show cultivars or environments that are more sensitive. Figure 2 shows the graph plotting the IPC1 scores against specific gravity. Table 6 shows the mean specific gravity and IPC1 scores using the AMMI model. These are the values that were transposed into the graph in Fig. 2. Cultivars and environments plotted closer to the x -axis proved to be more stable than cultivars and environments that lay further away from this axis. The further the values are from the x -axis, the more sensitive they are. Values close to the y -axis had average specific gravity scores. Values to the right of the y -axis had higher specific gravity values on average, while cultivars and environments on the left side of the y -axis had lower than average specific gravity scores. Cultivars and environments that are stable are less likely to be influenced by external variables. External variables are more likely to have an effect on the internal quality attributes, i.e. specific gravity, of cultivars and environments that fall within the sensitive category.

Table 5. Summary of data as used in AMMI Model for all cultivars and environments/production areas

	Identifier	Minimum	Mean	Maximum
Internal	SG	1.035	1.062	1.085
	DM (%)	11.22	16.66	22.35
	Chip colour	36.60	50.68	63.20
External (fertiliser)	Nitrogen (kg/ha)	239.6	286.9	363.0
	Phosphorus (kg/ha)	80	119.7	192.6
	Potassium (kg/ha)	67	217.2	496.9
External (evaluation)	Plants/ha	37,037	42,128	51,680
	Yield ton/ha	13.33	62.47	127.2
	Marketing Index	54.30	100.4	146.9
External (class, size and waste)*	Class 1	8.81	48.50	119.7
	Class 2	0	13.27	65.51
	Class 3	0	4.942	34.04
	Large	0	18.54	75.35
	Large-medium	1.93	15.83	45.29
	Medium	0	19.30	62.67
	Small	0	7.852	23.16
	Baby	0	3.474	14.16
	Waste	0	0.2084	4.410
External (weather)	Heat unit (°C)	1308	1868	2805
	Rainfall (mm)	0	350.2	763.1

*Values entered as % of total production region

Table 6. AMMI model for specific gravity showing ranked means and IPC1 scores

Cultivar		
	<i>Mean (SG)</i>	<i>IPC1 score</i>
Lanorma	1.064	0.0197
Markies	1.064	0.1006
Sifra	1.063	- 0.0437
Taisiya	1.060	0.0667
Valor	1.059	- 0.0428
Mondial	1.057	- 0.1005
Environment		
	<i>Mean (SG)</i>	<i>IPC1 score</i>
Tom Burke	1.0674	0.0271
Petrusburg	1.0717	- 0.0904
Cedara	1.0715	- 0.0569
Pietersburg 2017	1.0650	0.0120
Aurora	1.0647	- 0.0064
Pietersburg 2016	1.0608	0.1204
Ceres	1.0594	- 0.0285
Warden	1.0541	0.0243
Middelburg	1.0491	- 0.0176
Ugie	1.0466	0.0159

In Table 7, the AMMI score ranks are shown, together with the mean values for the following variables: plants per hectare, yield per hectare, marketing index, fertiliser, heat units and rainfall. Three separate environmental groups were identified from the AMMI ranks. The first group consists of Pietersburg 2016, Tom Burke, Warden, Ugie and Pietersburg 2017. In these five environments, Markies was the cultivar that consistently performed the best, i.e. obtained a rank of 1. Sifra was the most stable and scored the highest SG values when planted specifically in Aurora, Middelburg and Ceres. Mondial was the most stable with the highest SG values in Cedara and Petrusburg.

Table 7. AMMI scores and variables for IPC1

Environment	AMMI Rank						Variables Mean								
	Markies	Lanorma	Sifra	Valor	Mondial	Taisiya	Plants per ha	Yield	Marketing index	N	P	K	Heat Unit	Rainfall	
Pietersburg 2016	1	6	2	3	4	5	41666	52.22	103	250	81	128	2192	286	
Tom Burke	1	2	6	3	4	5	37037	59.03	104	301	142	106	2805	39	
Warden	1	2	3	6	4	5	41666	45.15	98.8	280	80	95	2409	577	
Ugie	1	2	3	6	4	5	44444	17.66	76.3	271	100	67	1345	445	
Pietersburg 2017	1	2	3	6	4	5	41666	57.88	124	250	81	128	1642	306	
Aurora	2	3	1	6	4	5	41666	97.11	97.6	313	193	497	2558	0	
Middelburg	3	2	1	4	5	6	44444	68.08	103	306	108	314	1414	76	
Ceres	3	2	1	4	5	6	51680	96.89	103	363	146	449	1463	24	
Cedara	3	2	5	4	1	6	37037	63.22	105	240	110	146	1308	640	
Petrusburg	3	5	4	2	1	6	37037	54.30	102	270	154	130	1642	306	

AMMI is a rank there is no unit associated. Plants per ha unit is per hectare. Yield is in ton/ha. Marketing index is a calculation that is described in Eq. 2. N, P and K is in kg/ha. Heat unit is a calculation that provides a unit as explained in Eq. 3. Rainfall is in mm

From Fig. 2, it can be seen that the following were the most stable environments: Ugie, Warden, Pietersburg 2017, Tom Burke, Middelburg, Aurora and Ceres; and thus, these areas produced cultivars that had consistent results for specific gravity. Petrusburg and Cedara were sensitive to external variables, as well as Pietersburg 2016, which was the most sensitive environment. It was observed that although the locality was the same for the two environments, Pietersburg 2016 and 2017, the heat units during 2016 were numerically higher which could be responsible for the sensitivity of the area in 2016. Tubers planted in these sensitive production areas delivered inconsistent results for specific gravity. The most stable cultivar was Lanorma, followed by Valor and Sifra. These three cultivars were the most stable in all the environments delivering consistent values for specific gravity. Taisiya was a more sensitive cultivar. Markies was the most stable in Pietersburg 2016, Tom Burke, Warden, Ugie and Pietersburg 2017. However, when all the environments are considered, Mondial and Markies were the most sensitive cultivars. These cultivars did not have consistent specific gravity results.

It must be noted that the one region, Warden, which was planted under dry land conditions did not perform significantly differently to production areas which made use of irrigation. This is in contrast to what was found in a study conducted in 2013 that found that tubers planted under dry land conditions differed significantly to tubers planted under irrigation. It

was found that tubers planted under irrigation tend to elicit more cultivar-specific characteristics, while tubers that were planted in dry land conditions tend to be similar in terms of textural properties (Booyesen et al. 2013). Furthermore, rainfall patterns are notoriously hard to analyse and difficult to use for obtaining significant statistical correlations. Average rainfall is a relative concept as the average rainfall may stay the same but other factors such as higher temperatures, increased evapotranspiration rates and the lengths of dry spells all exert effects on the true water availability (South African Weather Services 2019).

All climatic variables, be it individually or in combination, affect crop production and outcomes to some extent (Taylor 2018). As shown in Table 1, the production regions chosen fell over varying climatic regions according to the Köppen-Geiger climate classification map for South Africa (CSIR 2015). The grouping of the various production regions in the AMMI model had no correlation with climatic regions. This shows that climatic regions do not play a role in the textural properties but rather the specific internal and external variables.

Conclusion and recommendation

The textural properties of a potato are formed by a collection of variables, thus complicating the exact outcomes that a combination of external variables will have on the internal characteristics of the tubers. However, there are certain variables, such as heat units and water application, that affect quality parameters to a greater extent than other variables.

Specific gravity, dry matter and chipping colour were three internal quality attributes, which were explored in this study. External factors that were measured did not have a noteworthy effect on chipping colour while specific gravity and dry matter differed significantly between cultivars and over production areas.

This study showed that certain cultivars (Lanorma, Valor and Sifra) are less influenced by fluctuating agricultural and environmental conditions and thus deliver tubers of a more consistent quality irrespective of external factors. The internal quality attributes of cultivars Mondial, Taisiya and Markies were influenced to a greater extent by the external conditions.

An overall finding was that the environment had a greater effect on the internal qualities of the tubers than the specific cultivar type. Contrary to existing literature, cultivars in this study are not the main predictor of internal quality attributes, but environmental factors appear to play the major role. This study shows that cultivar classification may not be the ideal way to classify potatoes as environment has a greater effect on textural properties than intrinsic cultivar characteristics.

Textural classification needs to be done according to area/harvested specific tuber characteristics rather than only using cultivar as a predictor of culinary outcomes.

Acknowledgements

The grant holders acknowledge that opinions, findings and conclusion or recommendations expressed in any publication generated by the NRF-supported research are that of the author(s), and that the NRF accepts no liability whatsoever in this regard.

Potatoes South Africa

Funding

This work received funding from the Department of Science and Technology (DST)/National Research Foundation (NRF) South African Research Chairs Initiative (SARChI) in the National Development Plan Priority Area of Nutrition and Food Security (Unique Number: SARCI170808259212) and Potatoes South Africa

Declarations

Conflict of Interest

The authors declare no competing interests.

References

Abbas G, Frooq K, Hafiz IA, Hussain A (2011) Assessment of processing and nutritional quality of potato genotypes in Pakistan. *Pak J Agric Sci* 48(3):169–175

Anzaldúa-Morales A, Bourne MC, Shomer I (1992) Cultivar, specific gravity and location in tuber affect puncture force of raw potatoes. *J Food Sci* 57(6):1353–1356

AOAC (2000) Official method of analysis, 17th edn, Volume 1. Association of Official Analytical Chemists, Inc., Maryland

ARC (2019) ARC. Accessed March 5, 2019. <http://www.arc.agric.za/arc-iscw/Pages/Climate-Monitoring-Services.aspx>

Booyesen L, Viljoen AT, Schönfeldt HC (2013) A comparison of the eating quality of selected potato cultivars from two potato production regions in South Africa. *J Sci Food Agric* 93(3):509–516

CSIR (2015) CSIR. Accessed January 19, 2021. http://stepsa.org/climate_koppen_geiger.html

Daccache A, Key CA, Jones RJ, Weatherhead EK, Stalham MA, Knox JW (2012) Climate change and land suitability for potato production in England and Wales: impacts and adaptation. *J Agric Sci* 150(2):1–17

DAFF (2019) Department Agriculture, Forestry and Fisheries. Accessed November 12, 2019. https://www.google.com/search?client=firefox-b-d&sxsrf=ACYBGNTBZ-q1sRoz54LS3zmjonllHD-1jA%3A1573564607053&ei=v7DKXZb5AraJ1fAPiL2Q0Ag&q=potatoes+south+african+potato+class+size&oq=potatoes+south+african+potato+class+size&gs_l=psy-ab.3..33i160l4.6667.7244

DAFF (2013) Department of Agriculture, Forestry and Fishery. Accessed April 12, 2016. <http://www.nda.agric.za/daoDev/sideMenu/Food%20Import%20&%20Export%20Standard/docs/General%20requirements%20for%20grading%20,%20packing%20and%20marking%20of%20potatoes.pdf>

- Deguchi T, Iwama K, Haverkort AJ (2016) Actual and potential yield levels of potato in different production systems of Japan. *Potato Res* 59(3):207–225
- Ezekiel R, Singh B, Kumar D (2003) A reference chart for potato chip colour for use in India. *Indian Potato Assoc* 30:259–265
- Franke AC, Haverkort AJ, Steyn JM (2013) Climate change and potato production in contrasting South African agro-ecosystems 2. Assessing risks and opportunities of adaptation strategies. *Potato Res* 56(1):51–66
- Franke AC, Sekoboane IE (2021) Exploring Variability in Resource Use Efficiencies Among Smallholder Potato Growers in South Africa. *Potato Res* 64(2):213–228
- Gauch HG (2013) A simple protocol for AMMI analysis of yield trials. *Crop Sci* 53(5):1860–1869
- Hijmans RJ (2003) The effect of climate change on global potato production. *Am J Potato Res* 80(4):271–279
- Majeed A, Muhammad Z (2018) Potato production in Pakistan: challenges and prospective management strategies—a review. *Pak J Bot* 50(5):2077–2084
- McBratney A, Whelan B, Ancev T, Bouma J (2005) Future directions of precision agriculture. *Precision Agric* 6(1):7–23
- Oregon State University (2010) Oregon State University Agriculture. Accessed January 30, 2020. <http://www.dpi.vic.gov.au/agriculture/horticulture/vegetables/potatoes/potatoes-factors-affecting-dry-matter>
- Payne RW, Murray DD, Harding SA (2012) *GenStat® for Windows™ Introduction*, 15th edn. VSN International, Hemel Hempstead
- Potatoes South Africa (2019) Potatoes South Africa. Accessed February 5, 2019. <http://www.potatoes.co.za/>
- Raymundo A, Asseng S, Roberstson R, Petsakos A, Hoogenboom G, Quiroz R, Wolf J (2018) Climate change impact on global potato production. *Eur J Agron* 100:87–98
- Sato H, Koizumi R, Nakazawa Y, Yamazaki M, Itoyama R (2017) Data on the weights, specific gravities and chemical compositions of potato (*Solanum tuberosum*) tubers for food processing from different areas of Hokkaido, Japan. *Data Brief* 11:601–605
- Smith MF, Smith A (1992) The success of the AMMI model in predicting lucerne yields for cultivars with differing dormancy characteristics. *S Afr J Plant Soil* 9(4):180–185
- South African Department of Environment and Primary Industries (2000) South African Department of Environment and Primary Industries. Accessed March 15, 2019. <http://www.dpi.vic.gov.au/agriculture/horticulture/vegetables/potatoes/potatoes-measurement-specific-gravity>

- South African Weather Services (2019) Seasonal Climate Watch November 2019 to March 2020. South African Weather Services, Pretoria
- Steyn JM (2016) Resource use efficiencies and risks associated with potato production in South Africa. Potatoes South Africa, Pretoria
- Steyn PJ, Visser AF, Smith MF, Schoeman JL (1993) AMMI analysis of potato cultivar yield trials. South African Journal of Plant and Soil 10(1):28–34
- Taylor M (2018) Climate-smart agriculture: what is it good for? Peasant Stud 45(1):89–107
- Tein B (2009) The effect of different farming systems on potato tuber yield and quality. Agron Res 7(1):245–250
- Thybo AK, Szczypinski PM, Karlsson AH (2004) Prediction of sensory texture quality attributes of cooked potatoes by NMR-imaging (MRI) of raw potatoes in combination. J Food Eng 61(1):91–100
- UNDP (2019) United Nations Development Plan SDG's. Accessed January 12, 2019. <http://www.undp.org/content/undp/en/home/sustainable-development-goals.html>
- United Nations (2018) United Nations. Accessed May 15, 2018. <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>
- USDA (1977) United States Standards for Grades of Potatoes for Chipping. USDA, Washington
- van Niekerk C, Schönfeldt HC, Hall N, Pretorius B (2016) The role of biodiversity in food security and nutrition: a potato cultivar case study. Food Nutr Sci 7(5):370
- Walter A, Finger R, Huber R, Buchmann N (2017) Opinion: smart farming is key to developing sustainable agriculture. Proc Natl Acad Sci 114(24):6148–6150
- WHO (2018) Health, environment and climate change. WHO, Geneva
- Worthington CM, Hutchinson CM (2005) Accumulated growing degree days as a model to determine key developmental stages and evaluate yield and quality of potato in Northeast Florida. Proc Florida State Hortic Soc 118:98–101