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Effects of Field Selection Parameters and Specific Gravity on Culinary Evaluation Traits in a Potato Breeding Programme

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Abstract

Potato culinary evaluation is an integral component of a breeding programme to determine suitability of new cultivars to specific end-uses. In most breeding programmes, quality assessment is conducted after a few generations of field selection on tubers collected from the field or from storage conditions. In order to optimize selection procedures, we analysed the relationship between specific gravity of potato tubers and quality evaluation traits as well as the effects of field selection parameters in clones that are intended for fresh market and processing uses. A total number of 237 advanced breeding clones were analysed over three consecutive years in the potato breeding programme at Agriculture and Agri-Food Canada (AAFC). Principal component analysis (PCA) and linear mixed-effects model fit by maximum likelihood indicated that parameters used in field selection significantly contributed to specific gravity and culinary components. Specific gravity also contributed significantly to culinary traits related to acceptable quality of baked, boiled and French-fried products. However, such relationship was not observed for chip quality. Significant associations were found between field selection parameters, such as maturity, early vigour, top vigour, early harvest, tuber size and tuber appearance and culinary components related to French fry and chip quality, but not for quality of baked and boiled products. Broad-sense heritability estimates for various culinary evaluation traits ranged from 57 to 92%. The results suggest that specific gravity and culinary traits should be incorporated in early or intermediate generation selection parameters in order to optimize selection gains for specific end-uses.

Keywords Broad-sense heritability · Culinary traits · Field selection parameters · Linear mixed model · Principal component analysis · *Solanum tuberosum* · Specific gravity

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Introduction

Potato is an important food crop for human consumption due to its high yield and rich nutritional value (Camire et al. 2009). More than 377 million tonnes of potato tubers are produced worldwide annually (FAO 2018), and in developed countries, over 60% of potato production is used for processed products (Kirkman 2007). In potato breeding programmes, the culinary qualities of potato clones must be assessed in order to satisfy the requirements for both fresh and processing markets (Tai et al. 1985; Pereira et al. 1994; Tai and Coleman 1999). Several factors affect the culinary qualities of potato tubers. One of the most important factors is dry matter, which accounts for 13 to 37% of total potato weight (Gould 1999). The dry matter of the potato tuber is mainly composed of starch and can be estimated by measuring the specific gravity (SG) of potato tubers (Dale and Mackay 1994). Higher SG of tubers allows more processed products to be produced per unit and a better culinary quality of French fries (Johnston et al. 1970; Sayre et al. 1975). SG is strongly affected by environmental conditions and cultural practices such as rotation and nitrogen input (O'Sullivan 1978), as well as by the distribution of dry matter and the morphology of tubers (Louwes and Neele 1987). A number of studies have shown that potato yield and SG are negatively correlated in advanced tetraploid potato selections (Haynes et al. 1989; Haynes and Wilson 1991). SG is one of the most important selection parameters for internal quality of potato (Gould 1999) and often serves as the crucial indicator of processing quality and storability of potato tubers (Gould 1999; Shetty 2013). The latter is also affected by accumulation of reducing sugars during the storage treatment (Coffin et al. 1987; Biedermann-Brem et al. 2003; Zhu et al. 2010).

Potato breeding programmes use a series of agronomic characters as field selection parameters for potato selection before certain culinary parameters can be evaluated (Tarn et al. 1992; Bradshaw et al. 2009; Yuan et al. 2016). The latter involves some visual and sensory assessment of cooked tubers or processed products and heavily depends on the skilled judgment of evaluators. In order to optimize the breeding strategy, it is important to analyse the repeatability of ratings between different trials and entries and to gain a better understanding of the effects of these field selection parameters and interrelations with storage treatment, specific gravity and culinary traits. The objectives of this study were to analyse the contribution of specific gravity and field selection parameters to potato culinary components of quality traits evaluated in the Canadian potato breeding programme and to determine the broad-sense heritability of culinary traits for both fresh market and processing uses. This information is useful to optimize the selection scheme in a breeding programme.

Materials and Methods

Field Evaluation The study was conducted at the Benton Ridge Potato Breeding Substation of Agriculture and Agri-Food Canada's Fredericton Research and Development Centre during three consecutive years (2012–2014). A total number of 237 clones, including 57 French fry, 54 chipping and 126 fresh market types that survived 3 or 4 years of selection using selection parameters described below were used in comparison with 17 check varieties. Materials in the third field generation (50-hill evaluation trial) were generally repeated in the following year if the same clones were selected for advancement to the fourth field generation (100-hill evaluation trial). Field evaluation was conducted under rain-fed conditions. Benton Ridge (near Woodstock, New Brunswick, Canada) is located 67° 35 E and 45° 99 N at about 100 m above sea level. This site received an average of 600 mm of rain (532 mm, 673.2 mm and 416.8 mm in 2012, 2013 and 2014, respectively) during the potato growing seasons (May–September). Planting was done in mid-May, and harvest was conducted in late-September. After harvest, samples of marketable grade potato tubers were placed at room temperature for 1–2 weeks for skin curing and then stored in paper bags at 7 °C or 13 °C (± 0.5) with 80% humidity prior to culinary assessment.

Field Selection Parameters Eight different agronomic traits, including early harvest, early vigour, eye depth, maturity, top vigour, number of eyes, tuber appearance and tuber size, were recorded as field selection parameters each year (Table 1). These traits were chosen from more than 18 phenotypic characters assessed for selecting clones (Tarn et al. 1992). Traits were scored on a 1 to 9 scale where 1 was the lowest and 9 was the highest. These subjective data were compared to values obtained from the predicable reference checks. It is to be noted that maturity refers to vine senescence while the early harvest is calculated from the total yield of tubers from a five-hill plot harvested at 70–80 days after planting. The latter is an important selection parameter because it provides an indicator of early yield which allows growers or home gardeners to capture early markets that are often more lucrative. Detailed descriptions of the field traits assessed in this study have been outlined in our previous study (Yuan et al. 2016).

Specific Gravity Measurement Specific gravity was measured in September on approximately 5-kg samples taken after 1–2-week storage at room temperature. Values were

Table 1 Description of field selection parameters and their rating scales

Selection parameter	Description	Scale	Best check variety
Early_harvest	Total yield of 5 hills 70–80 days after planting	1–9	Early: Jemseg; late: Russet Burbank
Early_vigour	Estimate of the vigour 20–40 days after planting; 1 = very small, 5 = medium size, 9 = very large	1–9	Medium: Shepody; Yukon Gold
Maturity	Estimate of senescence 100 to 120 days after planting; 1 = extremely early, 5 = midseason, 9 = extremely late	1–9	Early: Jemseg; late: Russet Burbank
Top_vigour	Estimate of the vigour and size of the haulm; 1 = very weak, 5 = moderate, 9 = very strong	1–9	Weak: Jemseg; strong: Kennebec
Eye_depth	1 protruding, 9 very deep	1–9	NA
Number_eyes	1 very few, 9 extremely abundant	1–9	NA
Tuber_appearance	Based on tubers of marketable size with smoothness, type, uniformity, and general appearance; 1 = very poor, 5 = average, 9 = excellent	1–9	Chieftain, Yukon Gold
Tuber_size	Average size of the majority tubers in a field run condition; 1 = very small, 5 = medium size, 9 = over size	1–9	Kennebec, Shepody

calculated using the following equation: SG = (weight in air)/(weight in air-weight in water) (Tai et al. 1985; Gould 1999).

Boiling and Baking Culinary Evaluations After storage treatment, six tubers free from disease or damage were selected per entry for culinary evaluation (i.e. 3 used for baking and 3 for boiling). Potato tubers were rinsed thoroughly with tap water then air dried. Tubers used for boiling were first peeled and boiled in water for approximately 25 min. For baking, samples were placed on an oven rack and baked at 205 °C (400 °F) for approximately 60 min while doneness was checked with a metal probe. Samples were scored for each culinary component by a panel of trained evaluators. Scores for each component were then transformed into percentages of the total culinary values using a custom-designed computer program (Table 2).

Chips and French Fry Culinary Evaluations Chip quality evaluation was conducted in December from 13 and 7 °C storages, and after 4 weeks of reconditioning at 21 °C following storage at 7 °C. French fry evaluation was conducted in December and in February from 13 and 7 °C storages. After storage treatment, three tubers free from disease and damage were selected for culinary evaluation. For chips, tubers were sliced into discs of 1.0-mm thickness and five slices were selected from the centre of each of the three samples. The slices were rinsed with cold water in a colander to remove excess starch and blotted on paper towel to remove excess water. They were then fried in vegetable oil in an electric deep fryer. Cooking oil was held at 177 °C; frying was complete when bubbling ceased. Chips were visually assessed using AAFC colour chart cards, with ratings ranging from 10 (extremely dark) to 100 (extremely light). A chip score of 50 without any off-flavour is deemed acceptable. For French fries, tubers were sliced to 9.5 mm in strips with a French fry cutter. The strips were blanched in water at 88 °C for 7 min and then par fried in vegetable oil (Golden Premium Canola oil, Spectra Foods, QC, Canada) at 193 °C for 1 min and then flash frozen. Strips were finish-fried at 193 °C for 1½ min and then presented to panel members for scoring. Detailed culinary components and rating scales are presented in Table 2.

Statistical Analysis Broad-sense heritability (h^2) values of culinary traits were estimated on a phenotypic mean basis. Variances and standard errors for heritability were calculated using R according to the algorithm of Wricke and Weber (1986) and the equation $h^2 = \mathrm{var}(X)/[\mathrm{var}(X) + \mathrm{var}(X{:}YR)/3 + \mathrm{var}\,(\mathrm{RESIDUAL})/3]$ where X was the assessed value of line and YR represented year. Correlations among the culinary components were analysed using R codes of scatter plot of pair.panel (www.r-project.org) and qgraph described by Epskamp et al. (2012). Linear mixed-effects model fit by maximum likelihood built in R package lme4 was used to determine if the explanatory variables, both fixed and random effects, affect the response variables (Henderson 1982) and the simplest equation was displayed as V1~V2 + (1|V3) where dependent variable V1 was predicted by continuous variable V2, which was treated as a linear fixed effect, and V3, a random effect using the lmer syntax (Bates et al. 2015). Culinary components were treated as a response (dependent) variable, and all the selection parameters including specific gravity were considered as explanatory (independent) variables for the analysis. Year (YR) was considered as a factor while other parameters were calculated as continuous explanatory variables. The significance level of the assessment of the mixed model was displayed using R package car (www.r-project.org).

Table 2 Descriptions of culinary component traits and their rating scales

Quality trait	Substitute descriptor	Description of culinary component	Score	Percentage (%)
Bake	Bake_appe	Tuber appearance (1 excellent, 5 poor)	1–5	1–25
	Bake_disc	Tuber discolouration after 10 min standing (1 none, 5 extreme)	1–5	0–10
	Bake_off_fl	Off-flavour (1 none, 5 extreme)	1–5	0–20
	Bake_textur	Texture (1 extremely mealy, 7 extremely soggy)	1–7	3–45
	Bake_total	Sum of all bake		4–100
Boil	Boil_discol	Tuber discolouration (1 none, 5 extreme)	1–5	0–10
	Boil_mash	Appearance on mashed samples (1 excellent, 5 poor)	1–5	0–10
	Boil_off_fla	Off-flavour (1 none, 5 extreme)	1–5	0–20
	Boil_sloug	Sloughing on whole tuber (1 none, 5 extreme)	1–5	0–10
	Boil_textur	Texture on mashed sample (1 extremely mealy, 7 extremely soggy)	1–7	5–40
	Boil_whole	Appearance on whole tuber (1 excellent, 5 poor)	1–5	0–10
	Boil_total	Sum of all boil		5–100
Chip	Win13L	Chip Winter late (February) stored at 13 °C		10–80
	Win13E	Chip winter early (December) stored at 13 °C		10–80
	WIN7	Chip winter (December) stored at 7 °C		10–80
	Rcd4WK	Chip 4 weeks reconditioned at 21 °C after 7 °C storage		10–80
	CHIPavg	Chip average		0–240
French fry	F13XA	External appearance of French fry in February stored at 13 °C	1–5	4–20
	F13XT	Texture outside strips of French fry in February stored at 13 °C	1–5	4–20
	F13IT	Texture inside strips of French fry in February stored at 13 °C	1–5	6–30
	F13XC	External colour of French fry in February stored at 13 °C	1–5	2–10
	F13IC	Internal colour of French fry in February stored at 13 °C	1–5	4–20
	F13TOTAL	Sum of all French fry in February stored at 13 °C		20–100
	F7XA	External appearance of French fry in February stored at 7 °C	1–5	4–20
	F7XT	Texture outside strips of French fry in February stored at 7 °C	1–5	4–20
	F7IT	Texture inside strips of French fry in February stored at 7 °C	1–5	6–30
	F7XC	External colour of French fry in February stored at 7 °C	1–5	2–10
	F7IC	Internal colour of French fry in February stored at 7 °C	1–5	4–20
	F7TOTAL	Sum of all French fry in February stored at 7 °C		20–100
	D13XA	External appearance of French fry in December stored at 13 °C	1–5	4–20

Table 2 (continued)

Quality trait	Substitute descriptor	Description of culinary component	Score	Percentage (%)
	D13XT	Texture outside strips of French fry in December stored at 13 °C	1–5	4–20
	D13IT	Texture inside strips of French fry in December stored at 13 °C	1–5	6–30
	D13XC	External colour of French fry in December stored at 13 °C	1–5	2–10
	D13IC	Internal colour of French fry in December stored at 13 °C	1–5	4–20
	D13TOTA	Sum of all French fry in December stored at 13 °C		20–100
	D7XA	External appearance of French fry in December stored at 7 °C	1–5	4–20
	D7XT	Texture outside strips of French fry in December stored at 7 °C	1–5	4–20
	D7IT	Texture inside strips of French fry in December stored at 7 °C	1–5	6–30
	D7XC	External colour of French fry in December stored at 7 °C	1–5	2–10
	D7IC	Internal colour of French fry in December stored at 7 °C	1–5	4–20
	D7TOTAL	Sum of all French fry in December stored at 7 °C		20–100
	FFavg	French fry average		80–400

As another powerful statistical tool, Principal component analysis (PCA) was used to explore other latent relationships of specific gravity with the field selection parameters in the data set. PCA deciphers the original variables through linear combination and thereby reduces the dimensionality on the original dataset and generates a new set of uncorrelated PCs (Jolliffe 2002; Johnson and Wichern 2007). PCA was conducted using the procedure of prcomp algorithm (www.r-project.org) and the ggbiplot package for the visual display (Vu and Lei 2012).

Results

Correlations and Heritability Estimates of Culinary Components

Baking Correlations among culinary components and with specific gravity are presented in Fig. 1. The highest positive correlation was observed between bake texture and bake total score (0.84). Relationship between bake total score and other components, including bake appearance, bake discolouration and bake off-flavour were less pronounced (0.74, 0.40 and 0.36, respectively). Broad-sense heritability estimate for bake total value was 74% (Table 3).

Boiling Correlations were observed among various culinary components and with specific gravity in boiled samples (Fig. 2). The highest positive correlation was

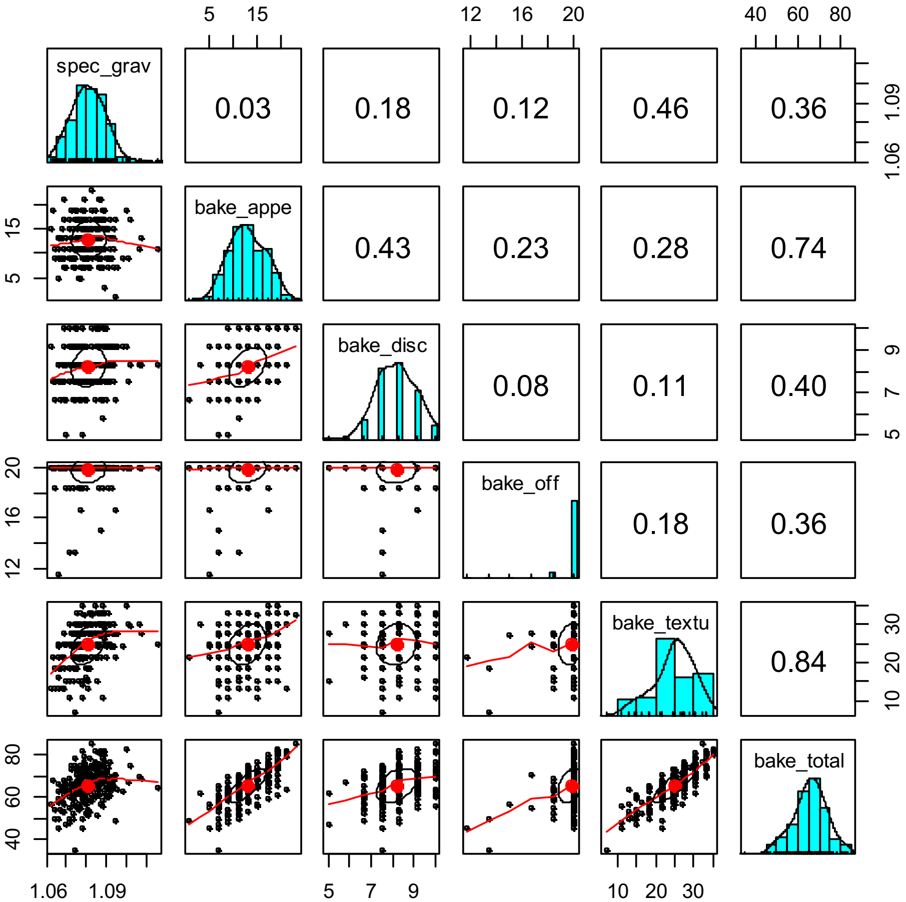

Fig. 1 Correlations of culinary components and specific gravity in baked products. The qgraph of correlation was generated using R program (Epskamp et al. 2012). spec_grav, specific gravity; bake_total, bake total scores; bake_textur, texture; bake_appe, appearance; bake_disc, discolouration; bake_off, bake off-flavour

identified between boil texture and boil total score (0.80). Positive correlations were also observed between boil total score with mashed sample appearance (0.60), boiled whole tuber appearance (0.50) and boil sloughing scores (0.40). Negative correlations were also found between specific gravity and boil discolouration (− 0.26) as well as boil whole tuber appearance (− 0.32). Broad-sense heritability estimate for boil total score was 68% (Table 3).

Chip The strongest correlation (0.93) was identified between average chip score and the score obtained after 4 weeks of reconditioning at 21 °C following storage at 7 °C. Correlations with other culinary components were also strong, including chip score in December at 13 °C and 7 °C without reconditioning. No significant correlation was identified between specific gravity and chip culinary components (Fig. 3). Broad-sense heritability estimates for mean average chip score and chip score in December at 13 °C were high, at 91% and 92%, respectively (Table 3). Chip score in December out of 7 °C storage and in February at 13 °C had the lowest heritability estimates (both 57%).

Table 3 Broad-sense heritability (h^2) estimates for culinary evaluation traits

Traits		σ^2_L	σ^2_{LY}	σ^2_R	h^2 (%)
French fry average		30.31***	19.24***	1.86	80.95
	D7TOTAL	46.93***	49.27***	0.93	73.74
	D13TOTAL	33.71**	74.08***	0.26	57.63
	F7TOTAL	20.36***	26.43***	11.06	61.95
	F13TOTAL	33.71***	20.73***	2.31	81.44
Chip average		80.95*	5.90**	19.44	90.50
	WIN7	28.29	0	64.23	56.92
	WIN13E	63.16*	0**	16.65	91.92
	WIN13L	23.19	24.21	28.44	56.92
	RCD4WK	38.25*	17.59*	10.09	80.58
Bake total		29.27***	18.09	12.80	73.97
Boil total		22.96***	25.90	6.55	68.02

*, ** and ***: Significant levels of mean square associated with variance components 0.05, 0.01 and 0.001 probability levels, respectively

$\sigma^2{}_L$: line variance; $\sigma^2{}_{LY}$: line × year; $\sigma^2{}_R$: error variance

French Fry In French fry evaluation, various culinary components were strongly correlated and showed association with specific gravity (Fig. 4). The sums of all French fry scores in February at 7 °C storage (F7T), as well as the sums of all French fry scores in December at 13 °C and 7 °C storages (D13T and D7T, respectively), showed strong positive correlations with the French fry average score (FFv). A positive correlation was also found between the sums of culinary components with their individual components such as F13T with F13XT, F13IC, F13XA and F13XC (Fig. 4). However, no direct association was identified between the sums of culinary components (D7T, D13T, F7T and F13T). High broad-sense heritability for French fry scores was observed in February at 13 °C storage (81%), whereas the lowest estimate was in December at 13 °C storage (58%) (Table 3).

Association of Culinary Components with Field Selection Parameters and Specific Gravity

Table 4 presents associations of culinary traits with the specific gravity and field selection parameters from the mixed-effects model fit by maximum likelihood using lme4 analysis (Bates et al. 2015). The relationship between culinary components and specific gravity varied considerably depending on cooking methods.

Baking Texture was strongly affected by specific gravity in the baked potato samples. Specific gravity significantly contributed to bake total and texture scores in the baking evaluation. The bake off-flavour, bake appearance and discolouration were not associated with specific gravity. The analysis also indicated that the culinary traits of baking were significantly affected by YR. However, no meaningful association was observed with field selection parameters (Table 4).

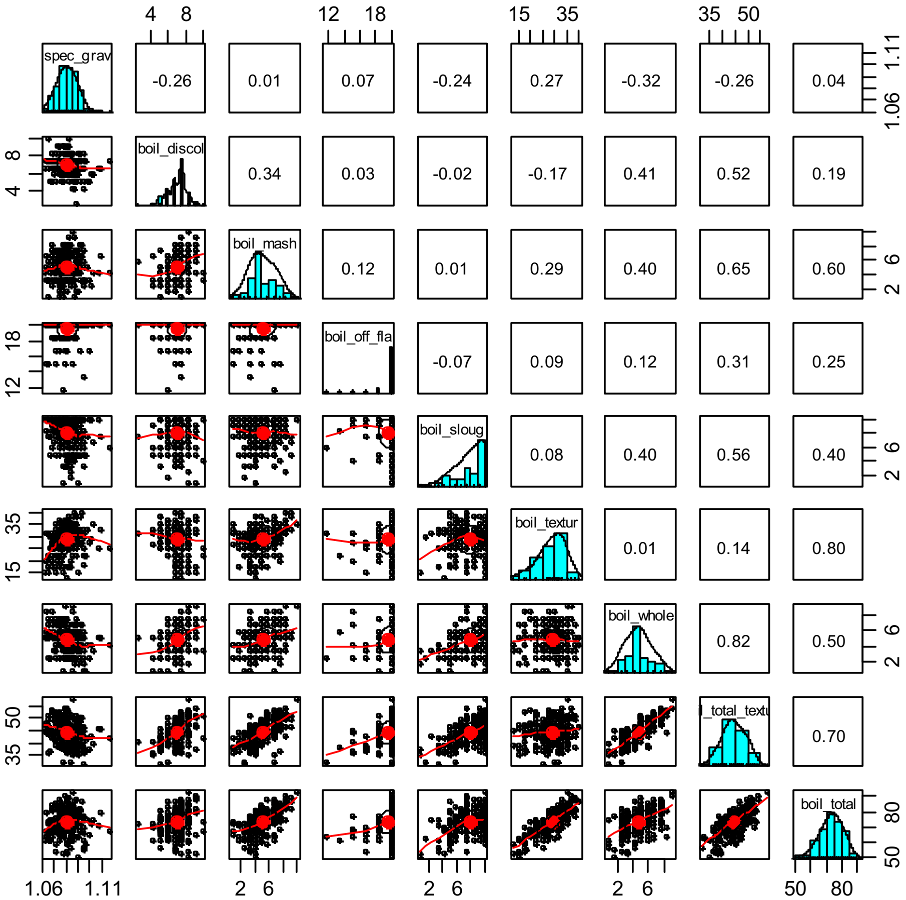

Fig. 2 Correlations of culinary components and specific gravity in boiled products. The qgraph of correlation was generated using R program (Epskamp et al. 2012). spec_grav, specific gravity; boil_total, boil total score; boil_discol, discolouration; boil_mash, mash; boil_off_fla, off flavour; boil_sloug, sloughing; boil_textur, texture; boil_whole, appearance on whole tuber

Boiling Texture in boiled potato samples was strongly affected by specific gravity. Sloughing, texture, discolouration and whole tuber appearance were all significantly affected by specific gravity. Appearance of mashed sample, presence of off-flavour and total boiling score were not significantly associated with the specific gravity. The analysis also indicated that the culinary traits of boiled products were significantly affected by YR and that no meaningful association was observed with field selection parameters.

Chip Significant associations were observed between maturity, early vigour, top vigour, tuber size and eye depth with some chip evaluation components. However, none of the chip culinary traits was associated with the specific gravity of potato tubers.

French Fry Significant associations were observed between culinary components and specific gravity and field selection parameters for French fry products (Table 4). The

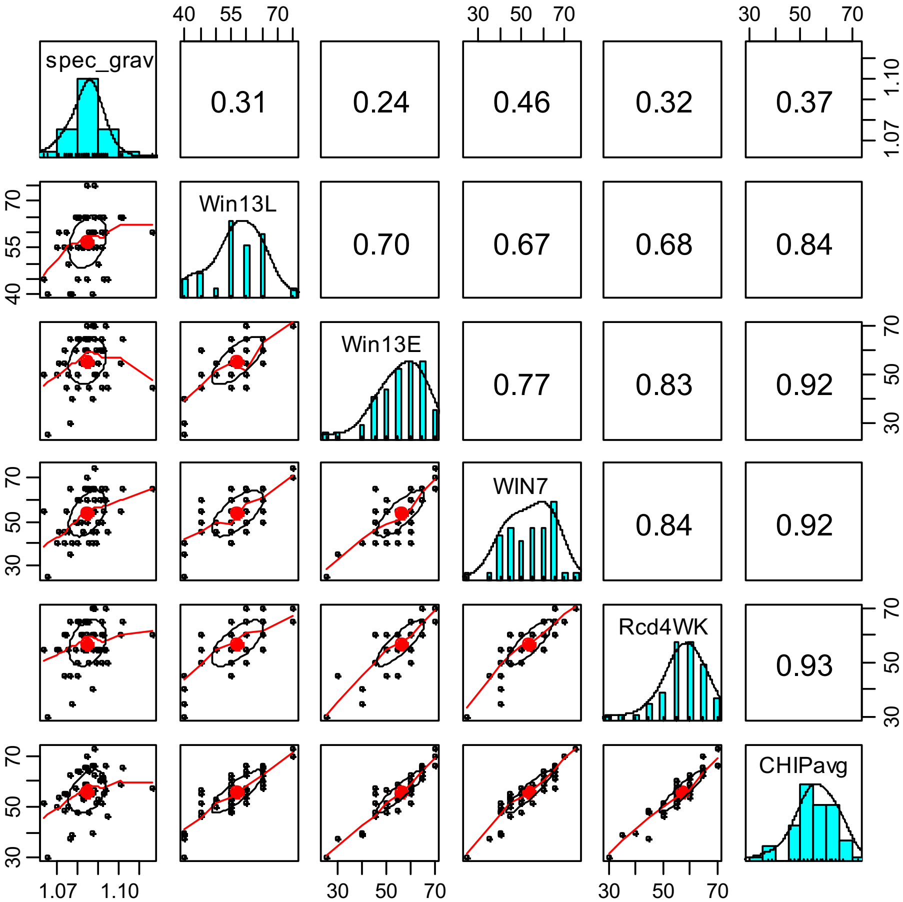

Fig. 3 Correlations of culinary components and specific gravity in chips products. The qgraph of correlation was generated using R program (Epskamp et al. 2012). spec_grav, specific gravity; CHIPavg, chip average; WIN7, chip winter (December) stored at 7 °C; Win13L, chip winter late (February) stored at 13 °C; Win13E, chip winter early (December) stored at 13 °C; Rcd4WK, chip 4 weeks reconditioned at 21 °C after 7 °C storage

total French fry value obtained in February at 7 °C storage displayed the highest association with specific gravity, followed by French fries from December storage at 7 °C. However, there was no association between the external fry colour and specific gravity in the February evaluation at 7 °C storage.

Further analysis was conducted using PCA to explore the relationships between specific gravity and field selection parameters in a multiple dimensional fashion. Results indicated that the first five PCs explained 73.8% of the total phenotypic variance in the population (Table 5). With the exception of eye depth and number of eyes, the remaining variables contributed positively to the first principal component (PC1) which accounted for 20% of the total variance. Both top vigour and YR contributed 0.439 to the variation. The second PC accounted for 17.9% of the total variation, and early vigour and top vigour also positively contributed to this component. The other selection parameters negatively contributed to this PC. The third PC

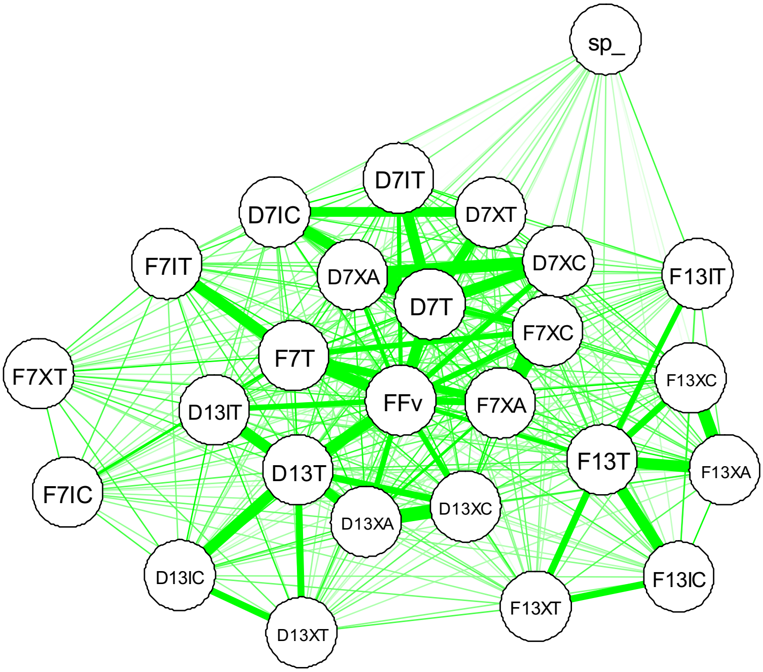

Fig. 4 Correlations of culinary components and specific gravity in French fry products. The qgraph of correlation was generated using R program (Epskamp et al. 2012). Green bar indicates the positive correlation between culinary components. A darker and bigger size of the bar indicates a more significant correlation. D13T and D7T are the sum of culinary components in December from 13 and 7 °C storages, respectively, while F13T and F7T represent the sum of culinary components in February. sp_, specific gravity; FFv, French fry average. The brief description of other culinary components is presented in Table 1

contributed 14.9% of the total variation. YR accounted (0.361) for the most variation in PC3 while other parameters negatively contributed to this principal component. PC4 accounted for 11.3% of the total variation, and tuber appearance was the largest contributor (0.698). Tuber size and YR also positively contributed to this PC. PC5 accounted for 9.8% of the total variation. Early harvest, eye depth, YR and early vigour positively contributed to PC5. A ggbiplot was used to visually display the two first PCs (Fig. 5). In the first PC, a clear correlation was observed among maturity, tuber size and early harvest.

Discussion

Culinary quality traits of potato tubers are important considerations in a potato breeding programme in order to determine new cultivars' market types and end-use suitability. The assessment of some culinary components such as flavour and texture is challenging due to low throughput and trait complexity (Taylor et al. 2007). Specific gravity of potato tubers is directly related to dry matter content, which affects the processing quality of potato tubers, cooking oil absorption and processing efficiency (Gould 1999; Bélanger et al. 2002). In our study, texture contributed up to 45% of the total score

Table 4 Association of quality traits and field selection parameters in culinary evaluations (2012–2014)

Quality trait	Cook value	YR	Spec_grav	Early_harvest	Early_vig	Maturity	Top_vigour	Eye_depth	Num_eyes	Tuber_app	Tuber_size
Bake	Bake_appe	***									
	Bake_disc										*
	Bake_off_fl										
	Bake_textur	**	***								
	Bake total	***	***							*	
Boil	Boil_discol		**								
	Boil_mash										
	Boil_off_fla										
	Boil_sloug	***	***								
	Boil_textur	***	***								
	Boil_whole	*	***								
	Boil_total-textur	***	***								
	Boil_total	***					*				
Chip	Rcd4wk										
	Win7	*			***		***	*			*
	Win13e	***				**		***		*	**
	Win13l	**						***			***
	Chip avg	***						***			
French fry	D7IC		***	**					*	***	
	D7IT	*	***	***	***	*	***	***		***	***
	D7XA	***	***	***	***	***	***	***	***	***	***
	D7XC	***	***	***	***	***	***	***	***	***	***
	D7XT		***	**						*	*

Table 4 (continued)

Quality trait	Cook value	YR	Spec_grav	Early_harvest	Early_vig	Maturity	Top_vigour	Eye_depth	Num_eyes	Tuber_app	Tuber_size
	D7total		***	**				*		***	
	D13IC	***	***	***	***	***	***	**	***	***	***
	D13IT	***	***	***		***		***	**	***	
	D13XA	***	***	***				***	**		**
	D13XC	***	***	***	**	***		***			***
	D13XT	*	*	***				***			*
	D13total	***	***	***	***		***	***	***	***	***
	F7IC	***	***	***	***	***	***	***	***	***	***
	F7IT	***	***	***	***	***	***	***	***	***	***
	F7XA	***	**	***	**	***		***	*	***	***
	F7XC	***		***		*		*	***	***	***
	F7XT	***	***	***	***		***	***	**	***	***
	F7total	***	***	**	***	***	***	***	***		***
	F13IC	***	***	***	***	***	***	***	***	***	***
	F13IT		***	***	**	**	*				
	F13XA	***	***	***	***	***	***	***	***	***	***
	F13XC	***	***	***		*	.			***	***
	F13XT	***	***	**	***	***	***		***	**	***
	F13total	***	***	***			*		***	***	***
	FF all	***	***	***	***	***	**	***	***	***	***

*Significant level: *< 0.05, **< 0.01, ***< 0.001

Table 5 Contribution of the first five principal components to the phenotypic variation in culinary evaluations using prcomp algorithm in R program (www.r-project.org)

	PC1	PC2	PC3	PC4	PC5
Specific gravity	0.376	− 0.064	0.439	− 0.274	0.235
YR[a]	0.439	− 0.020	0.361	0.108	0.267
Early_harvest	0.099	− 0.378	− 0.256	0.097	0.640
Early_vigour	0.373	0.401	− 0.402	− 0.181	0.128
Maturity	0.359	− 0.454	− 0.009	− 0.073	− 0.179
Top_vigour	0.439	0.264	− 0.396	− 0.313	− 0.144
Eye_depth	− 0.309	− 0.154	− 0.407	− 0.194	0.425
Number_eyes	− 0.043	− 0.387	− 0.128	− 0.424	− 0.396
Tuber_appearance	0.197	0.101	− 0.238	0.698	− 0.140
Tuber_size	0.242	− 0.483	− 0.233	0.250	− 0.195
Eigenvalue	1.413	1.339	1.221	1.062	0.988
Proportion of variance	0.200	0.179	0.149	0.113	0.098
Cumulative proportion	0.200	0.379	0.528	0.641	0.738

[a] YR represents year

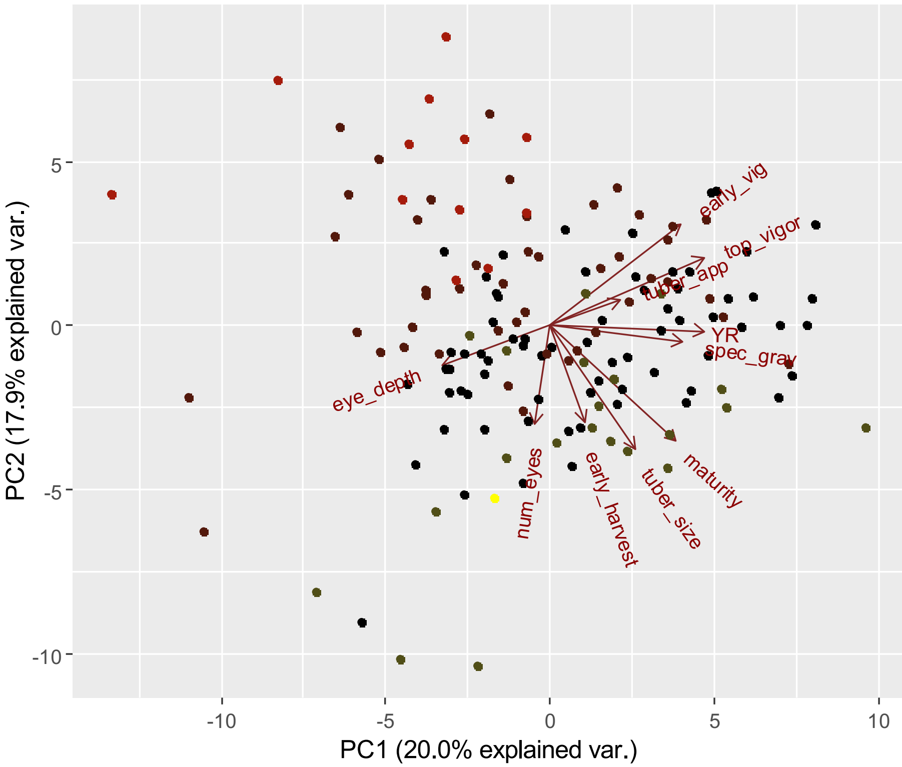

Fig. 5 Principal component analysis of specific gravity and field selection parameters in culinary evaluations. The plot was generated to display PC1 vs. PC2 using prcomp algorithm (cran.r-project.org) and ggbiplot of R program (Vu and Lei 2012)

among all culinary components. The texture of potato tubers is also a key culinary attribute that affects the acceptability of tubers for both fresh and processing industry. The texture of potato products was strongly affected by specific gravity in our study. Gould (1999) also suggested that specific gravity is correlated with dryness and mealiness of baked and boiled potato tubers. Positive correlation was identified between specific gravity and bake texture in baked products (Fig. 1). Unlike the texture of potato products that was strongly affected by specific gravity, the presence of off-flavour was not significantly associated with this trait in baked, boiled or mashed samples. Substantial off-flavours usually result in de-merits of affected clones in breeding programmes. Although the majority of culinary traits in baking and boiling showed a strong association with specific gravity, the total boil score did not show a significant association with specific gravity. However, when the boil texture was excluded from the total boil score, significant negative association was discovered, suggesting an antagonistic effect.

Various culinary traits for potato tubers showed differences in broad-sense heritability estimates. Chip score in December from samples stored at 13 °C showed the highest broad-sense heritability and its value showed a high correlation with average chip score. Based on these results, the December chip score appears to be a good indicator for overall chip quality. Some traits exhibited interaction variances (σ^2_{LY}) that were larger than line variances (σ^2_{L}) indicating genetic complexity and inherent difficulty in assessing these traits.

In our study, the chip colour evaluation exhibited the least value of the association with specific gravity. Previous studies (Tai and Coleman 1999) also indicated that there was no association between chip colour, specific gravity and marketable yield, and that chip quality is affected by agronomic practice and postharvest management. Therefore, besides high specific gravity being considered as an important parameter for tuber selection, chip quality is also affected by other contents of tubers.

In French fry quality assessment, nearly all of the culinary components were significantly associated with specific gravity. The highest association was observed with December fry score from 13 °C storage, whereas the lowest was identified for December French fry score from 7 °C storage. Therefore, specific gravity is a key selection parameter for clones destined to the French fry market.

Statistical analyses based on mixed model and PCA were used to investigate the association of specific gravity and field selection parameters of potato clones for quality traits. Substantial associations were identified between culinary components and the field selection parameters for French fry and chips but not for baked and boiled samples. Using PCA analysis, maturity and early-harvest yield were found to positively contribute to specific gravity. Our results showed that maturity, tuber size, top vigour and early vigour mostly contributed positively to PC1. Specific gravity is higher in late-maturating cultivars than that of early-maturing ones (Bélanger et al. 2002). However, eye depth negatively contributed to this PC suggesting that the first principal component increases with the decreasing value of the eye depth variable and that eye depth is considered as a negative trait for potato evaluation. This relationship could not be predicted using the mixed model, hence the importance of conducting complementary analysis. A strong association of specific gravity with year (YR) was observed across all of the quality traits indicating the influence of environmental conditions. The amount of precipitation in Benton Ridge area was variable with 532 mm, 673.2 mm and 416.8 mm recorded from May to September in 2012, 2013 and 2014. Top vigour and early vigour were found to have a positive value on PC2 while maturity, eye depth and number of eyes contributed similar negative value to this PC, suggesting that these variables affected specific gravity differently.

In conclusion, the analysis conducted in this study allowed us to decipher the contribution of specific gravity and field selection parameters to culinary components as well as relationships of specific gravity with field selection parameters. Not all of the culinary traits were similarly affected by specific gravity and field selection parameters. A thorough understanding of intrinsic relationships among various selection parameters is a pre-requisite for optimizing breeding strategies. Although specific gravity is critical factor for identifying clones suitable for French fry processing, this trait needs to be combined with many other traits in order to develop a marketable cultivar. Careful implementation of these parameters in a potato breeding programme is necessary in order to select cultivars better suited to different end-uses. Based on our analysis, specific gravity and culinary traits should be incorporated in early or intermediate generation selection parameters in order to optimize selection gains for specific end-uses. However, given the complexity of traits' assessment and low throughput, a more breeder-friendly tool such as marker-assisted selection is highly desired.

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