RESEARCH

Evaluation for fresh consumption of new broad bean genotypes with a determinate growth habit in central Chile

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Broad bean (*Vicia faba* L. [unranked] *major* (Harz) Beck) is usually consumed dry. In Chile, however, broad bean is grown as a vegetable crop with indeterminate genotypes. The new 'Alargá', 'Retaca' and 'Verde Bonita' broad bean genotypes, which have a determinate growth habit, were evaluated in six irrigated environments in central Chile at three locations (Rancagua, Talca, and Talagante) and on two planting dates (F1 and F2; 1-mo apart). The aim was to characterize their yield and select the best-yielding genotypes in terms of pod yield (PY) and fresh grain yield (GY). The best location(s) to produce fresh pods and fresh grain were also identified and described. Fresh grain yield and components were measured and the genotype × environment interaction (G×E) was analyzed. Pod yield differed among genotypes; 'Verde Bonita' and 'Retaca' had the highest PY (15 500 kg ha^{-1}, 8% higher than 'Alargá'). There was a G×E interaction for GY and 'Retaca' had its highest yield in Talca on the two planting dates and in Rancagua when planted late (F2). Mean GY of 'Retaca' was 3900 kg ha^{-1} with the highest number of grains per 1 m^2 (NG). The best GY was related to a higher seasonal photothermal quotient (ranging from 1.15 to 1.82 MJ m^{-2} d^{-1} °C^{-1}, r = 0.90, P ≤ 0.001). The lowest GY was in Talagante on F1. Genotypes differed in yield composition; 'Retaca' had many small pods giving many seeds per unit area and 'Verde Bonita' had large pods yielding fewer grains per unit area. The 'Retaca' genotype is preferred by the frozen broad bean industry, whereas 'Verde Bonita' is preferred by the fresh broad bean market.

Key words: Fresh faba bean, photothermal quotient, planting date, *Vicia faba* [unranked] *major*, yield components.

INTRODUCTION

Broad bean (*Vicia faba* L. [unranked] *major* (Harz) Beck) is grown in a variety of environments in latitudes ranging from 50° N to 40° S and altitudes from 0 to 3000 m a.s.l. This is due to the existence of a very diverse germplasm with distinct growing groups. One group is based on seed size (small and large). Another group is based on climatic adaptation including winter, spring, and Mediterranean types. Still another group is based on growth habit with determinate and indeterminate genotypes. Modern cultivars are grown in Australia, Canada, and European countries, while landraces are still grown in many countries (Gnanasambandam et al., 2012). Genotypes available worldwide vary in grain size and growth habit. Indeterminate genotypes with large grains are used in broad bean crops for human or animal consumption, but determinate genotypes with small grains are preferred for fresh consumption or frozen food.

The frozen food industry is interested in small broad beans for export to Europe where market demand is mostly for small grains (Nadal et al., 2000a). One way of producing small grains is to harvest large pod genotypes at an early development stage, but this practice usually results in lower yield and threshing difficulties (Nadal et al., 2000b). Genotypes with an indeterminate growth habit form pods late in the growing cycle as a consequence of the continuous development of vegetative structures that result in competition for nutrients, assimilation between vegetative and reproductive growth, and an increase in shading, which can induce abscission of the recently formed pods (Chbouki et al., 2005). In addition, harvest is complex and expensive in indeterminate genotypes because pods, which are at various stages of development, require several manual harvests to achieve similar size and quality. The lack of pod uniformity and the first pods developing too close to the ground in the indeterminate growth habit makes mechanical harvesting almost impossible (Nadal et al., 2000a; 2000b).

Some of the problems of indeterminate cultivars have been solved by breeding genotypes with a determinate growth habit, which is characterized by a terminal inflorescence after four to five flowering nodes and considerably reduced plant height and lodging. The terminal inflorescence trait, produced by the recessive *ti* gene (Nadal et al., 2004), has been incorporated into

a number of indeterminate broad bean genotypes. While the *ti* genotypes have lower biomass and lower yield potential than the conventional indeterminate germplasm, synchronous pod development facilitates mechanical harvesting of vegetable broad beans (Nadal et al., 2005; Gnanasambandam et al., 2012). In addition, these genotypes have a lower percentage of abscission (Chbouki et al., 2005) and a higher harvest index (HI) than indeterminate cultivars grown at similar plant densities (Gnanasambandam et al., 2012).

In Spain, Nadal et al. (2005) developed the determinate 'Retaca', 'Alargá' and 'Verde Bonita' genotypes, which are characterized by reduced height (80 to 90 cm) and fresh pod yield of approximately 8500 kg ha^{-1} (Nadal et al., 2004; 2005). The lower yield of the determinate genotypes can be compensated by increasing plant density (Filippetti and Robertson, 1991); this results in unproductive branches being replaced by a larger number of productive main stems per area (Chbouki et al., 2005).

The sowing date determines the photothermal environment of each crop throughout its cycle. Early plantings commonly have a better yield since they are associated with more photosynthesis throughout the growing cycle; therefore, there is increased DM accumulation, higher leaf area index, increased HI, more absorbed photosynthetic active radiation (PAR), and increased development of reproductive structures (Confalone et al., 2010). Early plantings also use winter rains better, particularly in Mediterranean rainfed areas where crop maturity is associated with periods of low to zero rainfall (Sau and Mínguez, 2000; López-Bellido et al., 2005). Andrade et al. (1993) showed that low temperatures, such as the ones experienced in early planting, decreased the conversion efficiency of the intercepted radiation to biomass, survival, and flower viability; however, early plantings extended the growing period and increased the amount of intercepted radiation by the crop. The effects of radiation and temperature in a given environment are expressed as yield in different species through the photothermal quotient (PTQ). High PTQ (high solar radiation at lower temperatures) throughout the growing cycle usually boosts yield as a result of a higher number of grains m^{-2} (Fischer, 1985; Slafer et al., 1994; Acevedo et al., 2002; Nalley et al., 2009). High solar radiation around anthesis increases photosynthesis, which is advantageous for yield. Conversely, a high temperature around the same period has a negative impact on yield since it shortens the period during which the number of grains is established in determinate crops (Nalley et al., 2009). Thus, temperatures above 19 °C at the onset of flowering and approximately 24 °C during the grain-filling period decrease yield (Turpin et al., 2003; Ajam and Vazin, 2011). A complicating factor is the presence of frost at early flowering that could cause flower and pod abscission with a subsequent yield loss; frost also produces tissue necrosis in larger pods, which affects the quality of the harvested product (Maqbool et al., 2010). Some authors recommend early planting only if there is no frost in the area and/or when the growing cycle of the genotype allows flowering in a frost-free period.

The recommended planting date in central Chile extends from April to June where May is the mean sowing date where the largest area of the crop is produced. Early plantings in mid-April are typically used for areas where the risk of frost at flowering is low (Tapia et al., 1995).

In dryland environments, indeterminate cultivars are preferred because they show higher yield stability (Sau and Mínguez, 2000), but determinate varieties are more suitable under irrigation (López-Bellido et al., 2005; Confalone et al., 2010).

In this study, we evaluated pod and grain yield of three Spanish fresh broad bean genotypes with a determinate growth habit in the irrigated central valley of Chile. Pod yield is of particular interest to the fresh broad bean market and fresh grain yield to the frozen broad bean industry. Our objectives were to characterize fresh grain/pod yield of determinate broad bean genotypes, select the best yielding genotypes in terms of pod yield (PY) and fresh grain yield (GY), and identify the best location(s) to produce fresh pods and fresh grains.

MATERIALS AND METHODS

Experimental procedure

The 'Alargá', 'Retaca', and 'Verde Bonita' genotypes were used for this study. They were bred in the Centro Alameda del Obispo of the Instituto de Investigación y Formación Agraria y Pesquera de Andalucía, Spain. Field trials were established at three locations and on two planting dates in 2007 in Chile's central valley (Table 1). Plants were established at a density of 286000 plants ha^{-1} on two planting dates for a total of six environments (Table 2). The objective of two planting dates (1-mo apart at each site) was to expose the genotypes to a range of climatic conditions expected to occur over time. Genotypes were tested in a randomized complete block design with five replicates in each environment; plot size was 35 m^2.

Plots were fertilized with N, P, and K based on soil analysis to reach 100, 80, and 120 units ha^{-1} of N, P, and K, respectively, in every soil. Experimental plots were kept weed-free with trifluralin (α,α,α-trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine) and linuron (3-(3,4-dichlorophenyl)-1-methoxy-1-methylurea) herbicides. Tolerance or resistance of the genotypes to pests and diseases were not evaluated; therefore, full protection of the crop was provided against *Botrytis fabae* and *Lyriomyza huidobrensis* with iprodione (3-(3,5-dichlorophenyl)-N-isopropyl-2,4-dioxoimidazolidine-1-carboxamide) and cyromazine (N-cyclopropyl-1,3,5-triazine-2,4,6-triamine). All plots were irrigated with irrigation tapes at a frequency determined on when the crop had used 30% of available

Table 1. Latitude, longitude, elevation, and soil physicochemical characteristics of the study locations.

Location	Code	Latitude	Longitude	Altitude	Soil taxonomy[1]	Depth	BD	AWC	pH	OM	EC
				m a.s.l.		m	g cm^{-3}	cm		%	dS m^{-1}
Rancagua	RAN	34°9'49" S	70°46'23" W	450	Fluventic Haploxeroll	70	1.49	5.65	7.3	2.8	0.92
Talca	TCA	35°31'10" S	71°27'17" W	110	Ochreptic Haploxeralf	85	1.14	9.02	6.3	7.5	0.60
Talagante	TLG	33°40'7" S	70°50'53" W	360	Fluventic Haploxeroll	40	1.49	6.56	8.1	3.0	1.85

The codes are the initials of the localities. BD: bulk density; AWC: available water content; OM: organic matter; EC: electrical conductivity.
[1]USDA classification.

Table 2. Description of the environments. Planting date, seasonal rainfall, accumulated solar radiation, thermal time (0 °C base temperature), and mean daily maximum, minimum and mean temperatures from emergence to fresh harvesting (grains with 75% water content).

Environment	Planting date	Rainfall	Radiation	Temperature			Thermal time	PTQ
				Max	Min	Mean		
		mm	MJ m^{-2}	°C			°C d	MJ m^{-2} d^{-1} °C^{-1}
RAN-F1	1 May	145.6	2 359.3	16.04	2.14	9.09	1 426	1.50
RAN-F2	8 Jun	59.2	2 353.7	16.34	2.51	9.43	1 112	1.82
TCA-F1	25 May	202.2	1 987.7	14.68	2.76	8.72	1 243	1.73
TCA-F2	3 July	94.1	1 932.5	16.42	3.51	9.97	1 118	1.61
TLG-F1	29 April	162.3	1 729.4	15.61	2.82	9.21	1 366	1.15
TLG-F2	5 June	75.1	1 613.8	15.87	3.06	9.47	1 084	1.24

RAN: Rancagua; TCA: Talca; TLG: Talagante; F1: Date 1; F2: Date 2; PTQ: photothermal quotient.

water at 15 cm soil depth as indicated by a Frequency Domain Reflectometry probe at each site. All plots were harvested when grains reached 75% water content, which occurred when grain equatorial diameter was between 8 and 11 mm. The environment was characterized for each location and planting date by describing weather and soil. Weather records included daily rainfall (mm), radiation (MJ m^{-2}), and maximum and minimum temperatures (°C). Thermal time (°C d) was determined with this information and 0 °C was the base temperature (Boote et al., 2002; Confalone et al., 2010). The photothermal quotient (PTQ) during the growth cycle (emergence to fresh harvest) was calculated according to

$$PTQ = [Rad/(Tmean - Tb)]$$

where *Rad* is the incident solar radiation during the growth cycle (MJ m^{-2}), *Tmean* is the mean temperature (°C), and *Tb* is the 0 °C base temperature.

Genotype yield was assessed by measuring fresh pod yield (PY), fresh grain yield (GY), and yield components: number of fresh pods (NP) and fresh grains per m^2 (NG), fresh 100-grain weight (W100G), and individual pod (PW) fresh weight. A 3 m^2 plant sample was obtained from each plot at harvest for these evaluations.

Statistical analysis
A combined ANOVA was performed for a randomized complete block design with a factorial arrangement where blocks were nested within the "environment" factor. The model was $Y_{ijk} = \mu + G_i + E_j + E_j > B_{k(j)} + G_jE_j + E_{ijk}$ where *Y* is the response variable, μ is the overall mean, *G* is the effect due to the genotype, *E* is the effect of the environment, $E > B$ is the effect of the nested blocks in each environment, G_jE_j is the effect of genotype × environment interaction (G×E), and *E* is the random error term. DGC multiple comparison tests were performed to detect differences among environments and genotypes.

We analyzed PY and GY of each broad bean genotype over the environments. A linear regression was performed for each genotype of the individual PY or GY on the mean PY or GY of all genotypes at each environment (environment index). Regression slopes less than or equal to 1.0 were considered as stable genotypes or genotypes with little variation among environments (Finlay and Wilkinson, 1963).

RESULTS AND DISCUSSION

Climatic and edaphic conditions
Weather variables for the six environments considered in this study are shown in Table 2. Rancagua (RAN) accumulated the highest level of solar radiation on planting dates 1 and 2 (RAN-F1, RAN-F2), followed by Talca (TCA) (TCA-F1 and TCA-F2). Talagante (TLG) had low solar radiation as compared with the other two locations (Table 2). Both RAN and TCA had the highest PTQ seasonal values. On average, genotypes on F1 were harvested after 148 d, whereas they were harvested after 102 d on F2.

Rainfall in all environments, except TCA-F1, was below 250 mm, which is the minimum requirement for rainfed broad bean in Mediterranean environments (Bryla et al., 2003). This experiment was irrigated and soil was kept close to field capacity; this is a common practice in Mediterranean regions to increase and provide stable broad bean yields (Oweis et al., 2005).

The soils in TLG and RAN were similar and were classified as Fluventic Haploxeroll. Their mean bulk density was 1.49 g cm^{-3}; OM was 2.8%, and AWC 5.65 cm (Table 1). Soil depth differed between these soils (40 and 70 cm, respectively) but broad bean is a shallow rooted crop with 60% of its roots in the top 15 cm of soil; therefore, the 40 cm soil depth of TLG was not considered

to be a limitation (Manschadi et al., 1998) for crop growth even with its higher salinity level (1.85 dS m^{-1}) as compared with the other soils (De Pascale and Barbieri, 1997). Soil at TCA was an Ochreptic Haploxeralf, a deeper soil with higher organic matter content due to its volcanic origin (Table 1). The pH of the three soils was within the range adequate for broad bean growth (Loos and Siddique, 1997). None of the soils at the study locations had important restrictions to grow this species.

Characterization of fresh grain and fresh pod yield and their interactions with the environment

Yields of the three broad bean genotypes evaluated over environments are shown in Table 3. Pod yield ranged from 7654 to 15,790 kg ha^{-1} and grain yield from 2108 to 4188 kg ha^{-1}. The G×E interaction was not significant ($P \leq 0.05$) for PY, but it was significant for GY ($P \leq 0.05$), as well as for individual pod weight (PW) ($P \leq 0.001$) and individual grain weight (W100G, $P \leq 0.05$). Number of pods m^{-2} (NP) and number of grains m^{-2} (NG) did not have a significant G×E interaction. Environmental effects were significant for all variables (P 0.001) as well as the genotypic effects, which were not significant only for individual grain weight (W100G) (Table 4).

The fresh broad bean market buys and sells fresh pods; therefore, pod yield (PY) is targeted. Pod yield of 'Verde Bonita' and 'Retaca' was statistically equal at each environment and 9% higher than 'Alargá' (Table 3). The

Table 4. Percentages of ANOVA sums of squares (SS) for yield and yield components. Block sum of squares and error are not included.

Source of variation	PY	NP	PW	GY	NG	W100 G
Environment (E)						
Planting Date (PD)	1.2 ns	6.7***	0.8*	8.7***	22.3***	0.1 ns
Location (L)	83.3***	5.9**	53.5***	59.7***	18.9***	93.8***
Genotype (G)	8.5**	79.1***	39.8***	22.0***	51.1***	0.5 ns
G×E						
PD×G	2.6 ns	3.4 ns	1.0*	0.8 ns	3.6 ns	0.2 ns
L×G	3.0 ns	3.0 ns	4.3***	5.4*	2.1 ns	1.8 ns
PD×L×G	1.5 ns	2.0 ns	0.6 ns	3.4 ns	2.1ns	3.6*

***$P \leq 0.001$; **$P \leq 0.01$; *$P \leq 0.05$; ns: non significant.
PY: Fresh pod yield; NP: number of fresh pods m^{-2}; PW: fresh pod weight; GY: fresh grain yield; NG: number of fresh grains m^{-2}; W100 G: fresh100-grain weight.
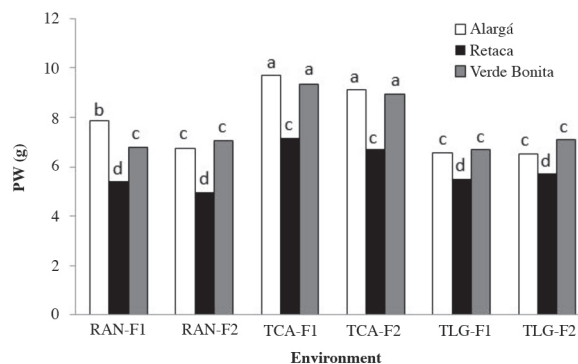
relevant yield components for PY are NP and PW. The number of fresh pods did not have a significant interaction with the environment since they are highly dependent on genotype; the NP sum of squares for genotypes was 79.1%, which is much higher than the effect of the environment (12.6%) (Table 4). 'Retaca' had a higher NP (26% and 41% more than 'Verde Bonita' and 'Alargá', respectively). The G×E of PW was highly significant (P ≤ 0.001, Table 5), but it had a lower proportion of the total sum of squares (5.9%), which was due to a change in genotype ranking in only one environment (Figure 1). However, PW was the lowest in 'Retaca' as compared with the other two genotypes and pod number was the highest in this genotype (Table 3).

Table 3. Yield and yield components of the tested genotypes across environments: fresh pod yield (PY), fresh grain yield (GY), number of pods m^{-2} (NP), individual pod weight (PW), number of grains m^{-2} (NG), and 100-grain weight (W100G).

Environment	Genotype	PY	NP	PW	GY	NG	W100 G
		kg ha^{-1}		g	kg ha^{-1}		g
RAN-F1	Alargá	10 444C	117E	7.9B	2340C	406D	56B
RAN-F1	Retaca	12 255B	198B	5.4D	3372B	591B	57B
RAN-F1	Verde Bonita	11 816B	147D	6.8C	2509B	483C	55B
Mean		11 505c	154c	6.7c	2740c	493d	56b
RAN-F2	Alargá	13 591B	181C	6.8C	3538B	646B	52B
RAN-F2	Retaca	13 011B	234A	5.0D	3707A	759A	51B
RAN-F2	Verde Bonita	13 479B	175C	7.1C	3356B	643B	57B
Mean		13 360b	197a	6.3c	3534b	683a	53b
TCA-F1	Alargá	14 446B	149D	9.7A	3838A	529C	68A
TCA-F1	Retaca	15 592A	224A	7.2C	4188A	706A	66A
TCA-F1	Verde Bonita	15 790A	168C	9.4D	3554B	565B	74A
Mean		15 276a	180b	8.8a	3860a	600b	69a
TCA-F2	Alargá	12 623B	138D	9.1A	3400B	517C	72A
TCA-F2	Retaca	12 133B	181C	6.7C	3806A	595B	73A
TCA-F2	Verde Bonita	13 097B	147D	9.0A	3154B	524C	71A
Mean		12 618b	155c	8.3b	3453b	545c	72a
TLG-F1	Alargá	7 654D	117E	6.6C	2108C	395D	54B
TLG-F1	Retaca	9 324C	169C	5.5D	2653C	521C	52B
TLG-F1	Verde Bonita	10 154C	151D	6.7C	2548C	494C	52B
Mean		9 044d	146c	6.3c	2436d	470d	53b
TLG-F2	Alargá	9 824C	150D	6.5C	2606C	508C	56B
TLG-F2	Retaca	11 527B	200B	5.8D	3271B	616B	54B
TLG-F2	Verde Bonita	11 637B	164C	7.1C	2973B	532C	52B
Mean		10 996c	171b	6.5c	2950c	552c	54b

Different uppercase letters in the same column indicate significant differences between genotypes ($P \leq 0.05$). Different lower-case letters in the same column indicate significant differences between environments ($P \leq 0.05$).
RAN: Rancagua; TCA: Talca; TLG: Talagante; F1: Date 1; F2: Date 2.

Table 5. Correlation matrix (r) for yield, yield components, and photothermal quotient (PTQ) of three determinate broad bean varieties.

	PY	GY	NP	NG	PW	W100 G	PTQ
PY	-						
GY	0.86***	-					
NP	0.49*	0.7**	-				
NG	0.64**	0.81***	0.94***	-			
PW	0.46*	0.19	-0.5*	-0.31	-		
W100G	0.56*	0.52*	-0.1	0.02	0.74***	-	
PTQ	0.90***	0.80***	0.39	0.60**	0.43	0.53*	-

***$P \leq 0.001$; **$P \leq 0.01$; *$P \leq 0.05$; ns: nonsignificant.
PY: Fresh pod yield; GY: fresh grain yield; NP: number of fresh pods m^{-2}; NG: number of fresh grains m^{-2}; PW: fresh pod weight; W100 G: fresh100-grain weight.
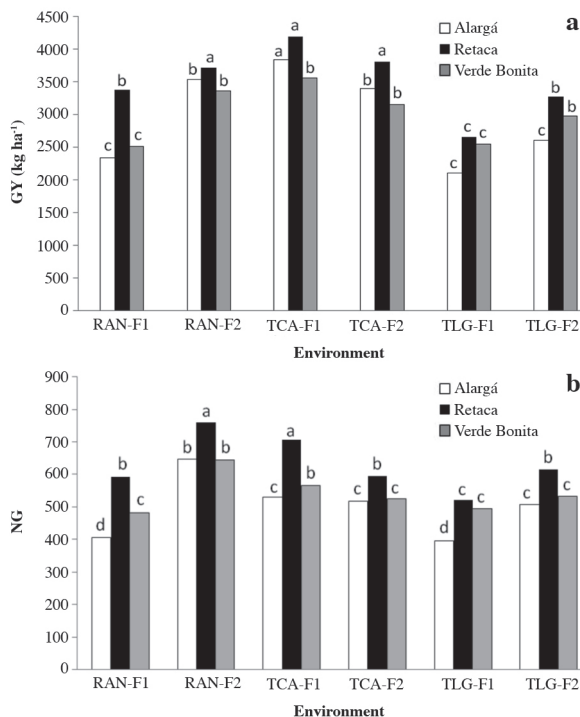

Figure 1. Fresh pod weight (PW) of 'Alargá', 'Retaca', and 'Verde Bonita' in six environments. G×E is caused only by RAN-F1. Different letters indicate significant differences (P ≤ 0.05).

RAN: Rancagua; TCA: Talca; TLG: Talagante; F1: Date 1; F2: Date 2.

Environmental effects were significant for PY and its components ($P \leq 0.001$) (Table 4). Talca's TCA-F1 was the best environment for fresh pod production with 2 300 kg above the mean PY of RAN-F2 and TCA-F2 and 6200 kg above TLG-F1, which was the environment with the lowest PY (Table 3). The highest PW was obtained at TCA-F1 and TCA-F2 with 2 g per pod higher than the other environments. The largest number of pods was produced in RAN-F2 and TCA-F1; this was 49% higher than TLG-F1 and RAN-F1, which had the lowest values.

The G×E interaction for GY was significant ($P \leq 0.05$, Table 4) and was due to a change of ranking in individual grain weight (W100G) since G×E of the number of grains m^{-2} (NG) was not significant. The percentage of the sum of squares attributed to the various sources of variation indicated that the observed variability of GY was mainly due to environmental effects (68.4%, $P \leq 0.001$). The genotypic effect was also significant ($P \leq 0.001$) and accounted for 22.0% of the total sum of squares, whereas the G×E interaction had the lowest effect (9.6%, $P \leq 0.05$). 'Retaca' had the highest fresh grain yield in all environments except TLG-F1 and TLG-F2 where its value was equal to 'Alargá' and 'Verde Bonita', respectively (Figure 2a). TLG-F2 had the lowest GY with a mean of 1400 kg less than GY at TCA-F1. 'Alargá' and 'Verde Bonita' had the same yield in each environment, except in TCA-F1 and TLG-F2 where 'Alargá' was the worst

genotype. 'Verde Bonita' had the lowest yield variation (this genotype had higher stability with a regression slope of 0.757) when changing from one environment to another; its yield was only 1000 kg when comparing the environment with the highest and lowest fresh grain yield. 'Alargá' had the highest variations (with the most unstable regression slope of 1.309) with differences of up to 1700 kg between the highest and lowest yielding environments (Figure 3a). Fresh grain yield depends on NG and W100G. The correlation is much stronger with NG (0.81 P 0.001) than W100G (0.52, $P \leq 0.05$) (Table 5). The G×E interaction of NG was not significant (Table 4) and the variability in NG was due to environment and
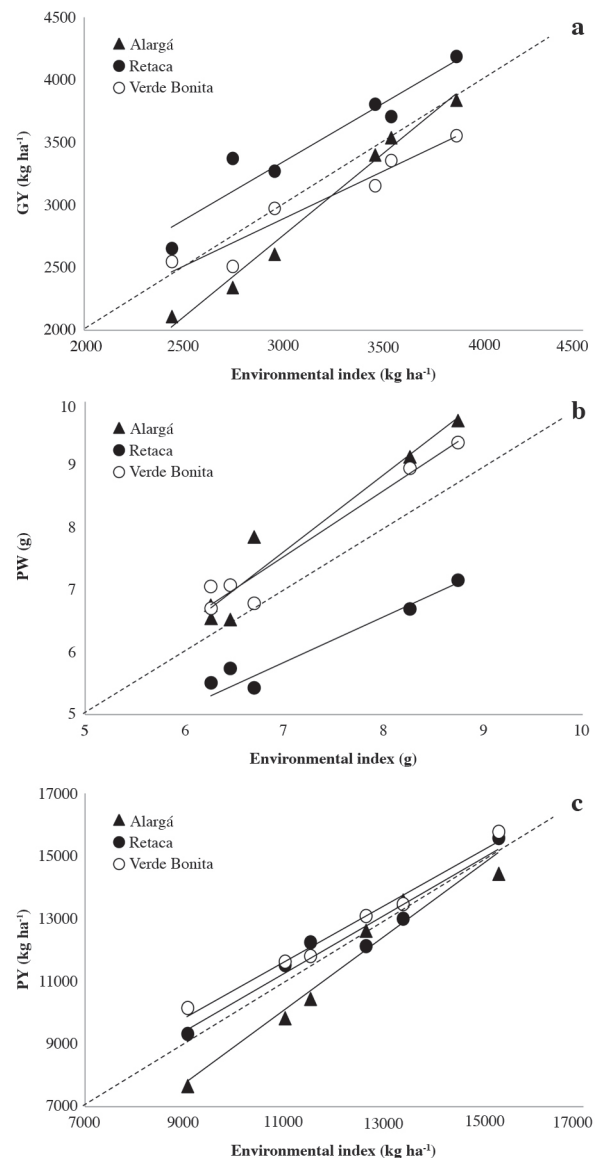

Figure 3. Regression of grain yield (GY) (a), individual pod (PW) weight (b), and pod yield (PY) (c) on environmental index (mean value of three genotypes in each environment). The dotted line corresponds to a 1:1 slope.

RAN: Rancagua; TCA: Talca; TLG: Talagante; F1: Date 1; F2: Date 2.

Figure 2. Fresh grain yield (GY) (a) and fresh grain per m² (NG) (b) of 'Alargá', 'Retaca' and 'Verde Bonita' in the six environments. Different letters indicate significant differences ($P \leq 0.05$).

genotype (41.2% and 51.1% respectively, Table 4). Even though the G×E interaction of W100G was significant (P ≤ 0.05), its share of the total sum of squares was low (5.6%). Considering that 'Retaca' GY was the highest in all environments and W100G was the same for the three genotypes in every environment, 'Retaca' NG was also the highest (Table 3); thus, 'Retaca' reached a high grain yield through a large number of smaller-sized pods which produced a large number of grains of the size similar to the other genotypes. On the contrary, 'Verde Bonita' reached its high yield through fewer larger pods (correlated to pod length, r = 0.64, P ≤ 0.05) with an intermediate number of grains (Table 3).

The environment that yielded more grains m^{-2} was RAN-F2 with a mean for the three varieties of 683 grains m^{-2}, which was 14% higher than TLG-F1 and RAN-F1 (Table 3). The environments that best discriminated between genotypes were RAN-F1 and TCA-F1 in which 'Alargá' exhibited the lowest NG value (Table 3).

As indicated above, there was no genotypic effect on the W100G yield component; however, the environments with higher W100G values were TCA-F1 and TCA-F2 with a mean of 69 and 72 g, respectively.

Genotypic effect

The fresh broad bean consumer is mostly interested in buying pods; 'Retaca' and 'Verde Bonita' were the genotypes with the highest PY across environments (Figure 3c). The higher PY of 'Retaca' was related to a significantly higher NP (r = 0.78, P ≤ 0.01). However, high PY of 'Verde Bonita' was related to high PW (r = 0.8, P ≤ 0.01, Table 3 and Figure 3b).

The frozen broad bean industry is mostly interested in fresh grain yield, which was the highest in 'Retaca' across environments. The highest GY of 'Retaca' was mainly due to the higher NG of this genotype (Figure 2b) and no genotypic effect on the W100G yield component (Table 4). This genotype produced a mean of 631 grains m^{-2} as compared with 540 and 500 grains m^{-2} produced by 'Verde Bonita' and 'Alargá', respectively. The correlation between grain yield and number of grains was 0.81 (P ≤ 0.001). Other authors have also found that the number of grains per unit area in broad bean is the yield component that has the best correlation with fresh grain yield (López-Bellido et al., 2005). The same applies to other legume crops (Poggio et al., 2005; Sandaña and Calderini, 2012).

Environmental effects

The environments that provided a better fresh yield for 'Retaca' and 'Verde Bonita' were TCA-F1, TCA-F2, and RAN-F2. This was probably due to their high PTQs (Table 2) as indicated by the positive significant correlation between PTQ and PY (r = 0.90, P ≤ 0.001), as well as GY (r = 0.80, P ≤ 0.001) (Table 5). The worst environments, TLG-F1 and TLG-F2, had the lowest values of accumulated solar radiation (1 671.6 MJ m^{-2})

and mean seasonal PTQ (1.20 MJ m^{-2} d^{-1} °C^{-1}) (Table 2). In addition, TLG-F1 was exposed to frost during the flowering stage with temperatures below -2 °C. This situation may have caused the abscission of reproductive structures, which is reflected in the lower fresh broad bean yield in this environment (Table 3).

Fresh grain yield was highly correlated with NG (r = 0.81, P ≤ 0.001) (Table 5), a factor that also showed a high correlation with NP (r = 0.94, P ≤ 0.001); 'Retaca' was the genotype with the highest values of these two yield components (Table 3). The PTQ, calculated during the crop cycle at each environment, was significantly correlated with NG (Table 5). These results are in line with those reported for other crops such as wheat (Fischer, 1985; Ahmed et al., 2010), pea (Poggio et al., 2005), and sunflower (Cantagallo et al., 1997).

Talagante was the site with lower pod and grain yield in both planting dates because this site had lower cumulative radiation and lower PTQ. Talca was the site with higher pod and grain yield, although TCA-F2 experienced a higher mean temperature during the plant's growing cycle, which caused shorter phenological stages; it reached harvest 40 d earlier than TCA-F1, which produced a decrease of up to 17% and 10% in pod and grain yield, respectively. Exposure to higher temperatures causes faster development in non-perennial crops; however, this does not result in an optimum for maximum yield because the shorter life cycle produces smaller plants, shorter reproductive phase, and reduced yield potential because of reduced cumulative light interception during the growing season (Hatfield et al., 2011). Bozoglu et al. (2002) reported that an increase in temperature after the beginning of flowering shortens both this period and the grain filling period; this produces a decrease of up to 25% in yield, which is generated by a reduction in the number of pods per plant and shorter pods. In our case, the correlation between the growth cycle and temperature was highly negative (r = -0.92, P ≤ 0.001). It is important to note that in the environments in which sowing was delayed 1-mo (F2) (Table 2), plants had a shorter growing cycle so that RAN-F2 and TCA-F2 reached harvest 53 and 43 d earlier than RAN-F1 and TCA-F1, respectively. However, RAN-F1 and TLG-F1 were the environments with the lowest GY for all three genotypes (Figure 2a), which was most probably due to frost as indicated above. The presence of frost during flowering increased blossom drop and reduced pod and grain yields (Table 3). Low temperatures occurred in the other environments during the vegetative stage when plants are more tolerant (Maqbool et al., 2010).

The RAN-F2, TCA-F1, and TCA-F2 environments had the highest values of accumulated solar radiation, which resulted in the highest PTQ values (1.72 MJ m^{-2} d^{-1} °C^{-1}) and varied in accordance with planting date. Planting date determines the PTQ under which the crop develops, especially during the critical period that determines yield

(Poggio et al., 2005). Fischer (1985) found that high PTQ values during wheat critical period (31 d before anthesis to 10 d after anthesis) maximize genotype yield. In indeterminate legume crops for dry grain consumption, the critical phenological stage to determine grain yield has been established between 10 d before anthesis and 50 or 40 d after anthesis; this parameter is highly correlated with the number of grains per 1 m^2 (Sandaña and Calderini, 2012). Harvesting of fresh pod/grain in the present study for determinate broad bean genotypes, we did not find similarity with the correlation found in indeterminate legume crops for PTQ during the critical period and NG; rather, we found a strong correlation between seasonal PTQ and NG, GY, and PY (Table 5). Solar radiation and temperature in this study had a high impact on broad bean yield through seasonal PTQ; this area warrants further study.

Results show that in Rancagua and Talagante, the northernmost sites (Table 1), planting should be in early June to optimize fresh yield, while in Talca, the southernmost site, planting could be advanced to the end of May.

CONCLUSIONS

This experiment has shown that determinate broad bean genotypes can be grown in central Chile and they have pod yield and grain yield similar or higher than values reported in comparable Mediterranean environments. There is genetic variability for pod yield and grain yield in the tested genotypes. Furthermore, yield formation changed according to genotype, which can have important implications for the crop's market orientation either as fresh or frozen products. 'Verde Bonita' and 'Retaca' were the genotypes with higher pod yields and 'Retaca' the highest grain yield. 'Retaca' appears to be the best candidate for the frozen food industry where the number of grains is the most important yield component in this industry. The best environments to grow determinate broad beans for fresh consumption are those with the highest seasonal photothermal quotients (high radiation at low mean temperatures), such as the RAN-F2, TCA-F1, and TCA-F2 study sites. Results also indicate that the yield of determinate genotypes may be more vulnerable to frost when it occurs at the flowering stage; therefore, a precise sowing date for a given location should be determined.

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