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ADAPTATION AND GENOTYPE x ENVIRONMENT INTERACTION OF FLAXSEED (*Linum usitatissimum* L.) GENOTYPES IN SOUTH CENTRAL CHILE

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ABSTRACT

Flaxseed (*Linum usitatissimum* L.) is imported into Chile mostly for bread making and feed. Identification of genotypes best adapted for seed production in South Central Chile would facilitate producer's decision. The objective of this study was to determine the adaptation and genotype x environment interaction of 16 flaxseed genotypes (including 10 from North American and six from Argentine sources) grown at 11 environments (defined as location-year) in Chile from 2003 to 2007. Genotype seed yield was above 5700 kg ha^{-1} for some environments indicating a high yield potential. According to the AMMI (Additive Main Effects and Multiplicative Interaction) and SREG (Sites regression) models the 11 environments were classified into four groups by the AMMI and three groups by the SREG models. Genotypes were classified into five groups by the SREG model with four of the groups as single genotypes. Overall mean seed yield was similar for all genotypes; however the genotype Nekoma was the most stable and higher yielding genotype across environments. The environment with the highest yield potential was Chillán 2003-2004, but this location had low yield stability across years. The environments with greatest seed yield potential, Chillán 2003-2004 and Los Ángeles 2004-2005, had irrigation during flowering and seed filling. Seed oil content fluctuated between 420 and 530 g kg^{-1}. The climatic differences among environments did not influence oil composition as expected from previous research. Flaxseed appears adapted to South Central Chile with differences observed among genotypes for biomass and seed yield, harvest index, test weight, oil content, and composition.

Key words: adaptation, genotype, seed yield, oil content, linolenic acid, *Linum usitatissimum*.

INTRODUCTION

Flax belongs to the Linaceae family and its origin is in Europe and Asia (Casa *et al.,* 1999; Charlton and Ehrensing, 2001; Berglund and Zollinger, 2002). Flax was introduced to the Americas by Spaniards, and brought to Chile at the beginning of the 19th century. Flax world production area is 2 339 210 ha. World average seed yield is 943 kg ha^{-1}, and Canada, India, China, and the USA are the main producing countries (FAO, 2009). Canada is the main flax seed exporter followed by the USA which together have 93% of the marketed volume in the World. The European Union is an important importer of flax seed (DIMEAGRO, 2007).

In Chile, there are only 50 ha of cultivated flax, mostly located in the South Central region of Chile. Chile imports 100% of the flax seed and flax oil consumed in the country. Most imported flax seed comes from Argentina, which produced 28 000 ha of flax in the 2006-2007 season (DIMEAGRO, 2007). Flax seed imported into Chile is used mainly for bread. Seeds have 400 to 420 g kg^{-1} of oil in most countries and the main fatty acids are alpha-linolenic acid (ALA), oleic acid, and linolenic acid (LA). Flax seed oil has approximately 50% of ALA and omega-3 fatty acid. The oil has a ratio of 1:3 between omega-3 and omega-6 fatty acids which is not easily found in other seed oils (Berglund and Zollinger, 2002). Flax seeds are sold for human consumption (nutraceutical and pharmaceutical industries) and also to feed poultry (chicken) and swine in Canada and the USA. Flaxseed oil is also used as industrial oil in varnishes and paints.

The human body does not synthesize ALA and LA which are required in the diet, thus they are called essential fatty acids. The ALA is required in the body to synthesize longer chain omega-3 fatty acids such as stearidonic acid, eicosapentanoic (EPA) and docosahexaenoic (DHA)

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acids. Flaxseed oil is highly reactive and easily becomes rancid. Only stabilized, encapsulated flax seed oil can be consumed directly by humans. The intake of flax seed and flax seed oil in humans and animals is limited by the presence of antinutritional factors (Madhusudhan *et al*., 1986; Oomah *et al*., 1996).

Flax is adapted to many environments mainly in temperate climates (Casa *et al*., 1999; Adugna and Labuschagne, 2003). It has been demonstrated that seed yield and seed yield components, plant height, time to reach harvest maturity, oil content, and oil composition, depend mainly on the temperature during plant development (Dybing *et al.,* 1988; D'Antuono and Rossini, 1995; Casa *et al*., 1999; Adugna and Labuschagne, 2003; Cross *et al*., 2003). Previous research indicated the oil content of flax seed decreased 40 g kg^{-1} when the day temperature increased from 15 to 27 °C and the night temperature increased from 10 to 22 ºC. Other factors such as seed moisture at harvest may also influence the final seed oil content and the oil composition (Froment *et al*., 1999; Adugna and Labuschagne, 2003).

The genotype x environment interaction is the result of the yield response of each genotype to the variations in soil fertility, water availability, temperature, photoperiod, light intensity, crop management, and other (Crossa *et al*., 1991). This interaction is a confounded effect of the genotype observed mean performance and its true value. Thus, the resulting phenotype and yield expression of a cultivated genotype will vary among environments due to their diversity of growth resources. This allows us to select the environment to which the genotype is adapted due to the differential adaptation in comparison with other genotypes evaluated simultaneously in the same environments (Romagosa and Fox, 1993; Diepenbrock *et al*., 1995; Adugna and Labuschagne, 2003).

In order to study the nature and magnitude of the genotype x environment (G x E) interaction and the adaptation of a genotype to a specific environment linear models (only additive effects) and bilineal models (additive and multiplicative effects) can be used. The additive main effect and multiplicative interaction (AMMI) and the sites regression (SREG) models have been used to analyze the G x E interaction (Zobel *et al*., 1988; Crossa *et al*., 1991; Crossa and Cornelius, 1997; Vargas and Crossa, 2000; Yan *et al*., 2000; Ma *et al*., 2004). The results of both models are displayed on biplots (Kempton, 1984). The AMMI results are displayed on a G x E biplot, and this enables determination of the main effect of the genotype, the environment, and the most meaningful G x E interactions. The SREG model is displayed as a GGE biplot (genotype, genotype x environment) based on the genotype main effect and the G x E interaction. This last model can be used for genotype evaluation, environment evaluation, and mega-environment analysis (Ma *et al*., 2004).

The objective of this study was to determine the adaptation and genotype x environment interaction of 16 flaxseed genotypes (including 10 North American and six Argentine sources) grown at 11 environments (defined as location-year) in south central Chile from 2003 to 2007.

MATERIALS AND METHODS

The experiment was conducted in Chillán, Yungay, Los Ángeles, and Osorno in the 2003-2004, 2004-2005, 2005-2006 and 2006-2007 seasons. Chillán (36°35' S, 72°04' W, 140 m.a.s.l.) is located in the Ñuble Province, Bío Bío Region, Chile. Soil at Chillán is medial, thermic Humid Haploxerands (Arrayán series), plain and good drainage and an average rainfall of 1000 mm (Carrasco, 1998). The climate of this location is classified as temperate Mediterranean and belongs to the agroclimate Chillán (Novoa *et al.,* 1989; Del Pozo and Del Canto, 1999). Yungay (37º03' S, 72º01' W, 263 m.a.s.l.) is located in the Ñuble Province, Bío Bío Region. Soil at Yungay is ashy, mesic Typic Haploxerand (Santa Bárbara series), slightly hilly and an annual rainfall from 1200 to 1500 mm the climate is classified as cold Mediterranean and the agroclimate is high foothills (Novoa *et al.,* 1989). Los Ángeles (37º27´ S, 72º18´ W, 210 m.a.s.l.) is located in the Bío Bío Province, Bío Bío Region. The soil at Los Ángeles is ashy, mesic Typic Haploxerand (Santa Bárbara series), slightly hilly with an annual rainfall from 1000 to 1500 mm. The climate is classified as temperate Mediterranean and belongs to Chillán agroclimate (Del Pozo and Del Canto, 1999).

Osorno is located (40º22' S, 73º04' W, 72 m.a.s.l.) in Los Lagos Region, Chile. The experiments were conducted under dryland conditions and no-till. Soil at Osorno is ashy, mesic Typic Haploxerand (Osorno series), slightly hilly and rainfall from 1200 to 1500 mm. Climate is classified a cold Mediterranean (Novoa *et al.,* 1989). The chemical and physical soil analysis and the average monthly temperature and rainfall of each environment are indicated in Table 1.

Experiments management

All environments had 16 genotypes except in Yungay 2003-2004, which had only 10 genotypes. Experimental units consisted of six rows, 5 m long and spaced 20 cm apart. Ten of the genotypes tested were from the USA and six from Argentina. Genotypes and their characteristics are indicated in Table 2.

Seeding dates, seeding rates, fertilizer rates, and harvest dates are indicated in Table 3. All fertilizers

Table 1. Mean monthly temperature and soil analysis of 11 environments during the growing seasons 2003-2004, 2004-2005, 2005-2006, and 2006-2007.

	Environments									
	Chillán				Yungay		Los Ángeles	Osorno		
Months	**03/04**	**04/05**	**05/06**	**06/07**	**03/04**	**04/05**	**04/05**	**03/04**	**04/05**	**06/07**
	Mean monthly temperature (ºC)									
Aug.	8.7	9.2	9.4	9.7	-	-	-	-	-	-
Sept.	10.9	11.2	10.5	10.8	12.7	-	-	9.4	9.1	8.9
Oct.	13.4	12.3	13.3	12.8	15.9	-	-	11.4	10.6	10.3
Nov.	15.9	15.4	16.6	15.9	18.1	-	-	13.3	13.2	12.3
Dec.	16.8	17.9	18.3	17.3	19.1	-	-	12.8	14.7	14.7
Jan.	20.3	19.6	20.0	20.0	22.5	-	-	16.5	15.5	16.2
	Monthly rainfall (mm)									
Aug.	84.9	87.0	250.9	172.1	-	-	-	173.5	-	-
Sept.	85.3	57.4	37.0	56.6	56.4	-	-	105.9	56.7	106.4
Oct.	61.9	83.3	19.0	89.4	57.8	-	-	92.9	28.8	144.2
Nov.	76.3	45.0	19.3	2.3	59.4	-	-	59.6	85.1	41.9
Dec.	24.6	59.8	37.2	66.6	20.6	-	-	15.4	30.7	100.7
Jan.	0.0	0.0	24.9	0.0	0.0	-	-	0.0	89.2	18.9
Soil analysis										
pH	6.0	6.2	6.2	6.3	5.9	-	-	5.28	4.20	5.03
Organic matter, %	3.0	5.2	4.6	5.9	10.3	-	-	6.39	7.60	5.79
$N\text{-}NO_3$, mg kg^{-1}	10.0	2.5	62.5	7.5	7.0	-	-	28.00	9.30	10.00
P Olsen, mg kg^{-1}	31.0	38.0	55.3	50.8	6.3	-	-	35.30	27.70	18.70
K disp., mg kg^{-1}	400.0	448.3	419.3	704.9	112.6	-	-	536.10	200.90	262.60

Temperature and rainfall data from Meteorological Station, Experimental Station El Nogal, Campus Chillán, Universidad de Concepción; Meteorological Station El Carmen, Departamento de Suelos, Universidad de Concepción; Meteorological Station, Instituto de Investigaciones Agropecuarias INIA, Osorno, Región de Los Lagos, Chile.

were applied and then incorporated in furrows at 4 cm depth at seeding. The experiments were conducted under conventional tillage and with supplemental irrigation at Chillán and Los Ángeles, and dryland conditions and no-till at Yungay and Osorno. The previous crop was wheat (*Triticum aestivum* L.) at all environments. Fertilizer rates were calculated at each location according to soil analysis. Broadleaf and grass weeds were controlled with pre-plant incorporation of trifluralin [2,6-dinitro-N,N-dipropyl-4-(trifluoromethyl)benzenamine] at 1 L ha^{-1} (Treflan, Dow Agrosciences, Chile). Post-emergence broadleaf weed was controled with MCPA dimethylamine salt at 0.46 L ha^{-1} (MCPA 750SL, ANASAC, Chile), and for grass weeds quizalofop-p-tefuryil at 0.275 L ha^{-1} (Pantera Plus, Crompton Corporation, Chile). Yungay and Osorno plots were hand weeded. In Chillán in 2003-2004 and Los Ángeles in 2004-2005, flax was irrigated by furrows; irrigation frequency was every 7 d replacing about 70% of pan evaporation. The two-center rows of each plot were swathed and threshed with a stationary plot combine (Bill's Welding, Pullman, Washington, USA).

Evaluations

Biomass samples were taken from a 0.2 m^2 area within each plot where plants were cut at the stem base. Harvest index was calculated as percentage of dry seed weight divided by total dry aboveground biomass from the 0.2 m^2 harvested area within each plot. Biomass and harvest index were determined only in Chillán, Yungay, and Osorno in 2003-2004. One thousand seeds were counted with an electronic seed counter and weighed to determine 1000 seed weight. Test weight was calculated by determining the weight of 100 mL of seed from the harvested seed yield of each plot. Seed yield was taken from the center-two rows of each experimental unit discarding 0.5 m of plants from row ends. Seed oil content was determined on a 40 mL sample of each experimental unit with a Newport Nuclear Magnetic Resonance (NMR) analyzer, (Newport 400, Oxford Institute, Oxford, England).

Table 2. Flaxseed genotypes description.

Genotype	Authors	Origin/ year	Days to flowering	Seed size	Color		Oil content	Plant height
					Flower	Seed		
							%	cm
Bison	Hammond *et al*., 1991	ND-04	-	-	-	-	-	-
Cathay[1]	Hammond *et al*., 1991	ND-97	54	Med.	Blue	Brown	40.2	53
Linott[1]	Miller *et al*., 1988	Can-66	48	Med.-Small	Blue	Brown	39.7	50
Neche[1]	Hammond *et al*., 1991	ND-88	51	Small	Blue	Brown	39.9	50
Nekoma[1]		ND-02	52	Med.- Small	Blue	Brown	40.1	51
Omega[1]	Miller *et al*., 1992	ND-90	52	Medio	Blue	Gold	39.8	49
Pembina[1]	Miller *et al*., 1988	ND-97	53	Med.- Small	Blue	Brown	39.7	52
Prompt[1]	Grady and Lay, 1994	SD-89	46	Small	Blue	Brown	39.7	47
Rahab[1]	Grady *et al*., 1987	SD-94	53	Medium	Blue	Brown	40.3	49
York[1]	Grady and Lay, 1994	ND-02	54	Medium	Blue	Brown	39.3	49
Carapé[2]	INTA	Argentina	-	Medium	Blue	Brown	-	-
Lucero[2]	INTA	Argentina	-	Medium	Blue	Brown	-	-
Omega Arg.[2]	INTA	Argentina	-	Medium	Blue	Gold	-	-
Tape[2]	INTA	Argentina	-	Medium	Blue	Brown	42.5	68
Salto[2]	INTA	Arg-85	-	Medium	Blue	Brown	43.7	67
Rojas[2]	INTA	Arg-85	-	Medium	Blue	Brown	44.3	67

[1]United States genotypes (Grady y Gilbertson, 2009).
[2]Argentine genotypes (INTA Argentina).
ND: North Dakota; SD: South Dakota; Can: Canada; Arg: Argentina.

Seed fatty acid composition analysis was conducted at the Facultad de Ingeniería Agrícola, Universidad de Concepción. Gas chromatography of methyl esters was performed with a gas chromatographer (Varian 3900, Varian, Palo Alto, California, USA), equipped with a flame ionization detector (FID). Analysis was conducted on a CP-WAX 52 CB 30 x 0.25 mm silica gel column. The analysis was conducted as follows: column flow 1 mL min^{-1} programmed ramp at 120-240 ºC in three stages 120 ºC for 3 min, and increasing at 3 ºC min^{-1} to 210 ºC, for 55 min, and a final increase of 15 ºC min^{-1} to 240 ºC for 65 min. Injector and detector temperatures were set at 200 and 300 ºC, respectively (Ackman, 2002).

Table 3. Seeding dates, seeding rates, N, P, rates applied, and harvest dates of the 11 environments evaluated.

Location	Year	Seeding date	Seeding rate	Fertilization			Harvest date
				N	P_2O_5	K_2O	
				kg ha^{-1}			
Chillán	2003/2004	14 Aug. 2003	24	75	200	80	27 Jan. 2004
	2004/2005	4 May 2004	35	75	100	80	-
	2004/2005	23 Aug. 2004	35	75	100	80	21 Feb. 2005
	2005/2006	9 Sept. 2004	35	75	100	80	19 Jan. 2006
	2006/2007	19 May 2006	35	125	100	80	27 Feb. 2007
Los Ángeles	2004/2005	30 Aug. 2004	35	75	100	80	15 March 2005
Yungay	2003/2004	10 Aug. 2003	24	24	150	113	13 Feb. 2004
	2004/2005	5 Oct. 2004	35	75	100	80	18 Feb. 2005
Osorno	2003/2004	25 Aug. 2003	-	60	70	50	24 Feb. 2004
	2004/2005	22 Sept. 2004	35	75	100	80	25 Feb. 2005
	2006/2007	12 Sept. 2006	35	125	100	80	2 March 2007

Experimental design and statistical analysis

The experimental design was a randomized complete block design (RCBD) with four replicates at the 11 environments tested. Statistical analyses were conducted using standard procedures for a randomized complete block design at each environment (Steel *et al*., 1996). The SAS system was used to process the data (SAS Institute, 2007). Each combination of location-year was defined as an "environment" and considered a random effect. The fall and spring seeding at Chillán 2004-2005 were considered separate environments. Genotypes were considered fixed effects. Mean separation was performed by applying *F*-protected least significant difference (LSD) comparisons at $P \leq 0.05$ level of significance.

Analysis of Genotype x Environment interaction

The genotype by environment data analysis was performed using the AMMI and SREG models. Two types of biplots, AMMI biplot (Zobel *et al*., 1988) and GGE biplot (Yan *et al*., 2000; 2007) were used to visualize the genotype by environment interaction. For this analysis the 10 genotypes from the USA and 11 environments were used.

The bilineal AMMI model is represented by:

$$Y_{ij} = \mu_j + \delta_i + e_j + \sum_{k=1}^{t} \lambda_k \, \alpha_{jk} \gamma_{kj} + E_{ij} \qquad [1]$$

And the lineal-bilineal SREG model is represented by:

$$Y_{ij} = \mu_j + e_j + \sum_{k=1}^{t} \lambda_k \, \alpha_{jk} \gamma_{kj} + E_{ij} \qquad [2]$$

where Y_{ij} is the seed yield of genotype i in environment j; μ_j is the mean value in environment j; $i = 1…g$; $j = 1….e$, g and e being the number of genotypes and environments respectively; and t is the number of principal components (PC) used or retained in the model, with $t \leq \min(e,g\text{-}1)$; g_i is the effect of the genotype; a_j is the effect of the environment; λ_k ($\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_t$) are the eigenvalues of each principal component retained in the model. The model is subject to orthonormality constraints on the eigenvectors of the genotypes [$\alpha_{ik} = (\alpha_{1k},\ldots,\alpha_{gk})$] and the eigenvectors of the environments [$\gamma_{kj} = (\gamma_{k1},\ldots,\gamma_{ke})$], where $\sum_i \alpha^2_{ik} = \sum_j \gamma^2_{kj} = 1$ and $\sum_i \alpha_{ik} \sum_i \alpha_{ik'} = \sum_j \gamma_{kj} \sum_j \gamma_{kj'} = 0$ for $k \neq k'$; α_{ik} *y* γ_{kj} for $k = 1, 2, 3…$ are called primary, secondary, tertiary and so on, effects of genotypes and environments and E_{ij} is the error. The AMMI biplot allows the visualization of the main effects of the genotypes and of the environments, in addition to the most important G x E interactions. The GGE biplot allows visualization of the genotype x environment interaction, and the relationship among genotypes and among environments. The AMMI biplot was constructed with the first PC in the *y* axis and seed yield in the *x* axis. The GGE biplot was constructed using the first two PC (PC1 and PC2) derived from subjecting the environment-centered data to singular-value decomposition (Ma *et al*., 2004). The GGE allows visualization of the which-won-where pattern (i.e., which genotype has the highest yield in which environment), also allows simultaneous visualization of the mean performance and stability of the genotypes, the discriminating ability of a specific environment, and the interrelationship among environments (Yan, 2001; 2002) The analysis was conducted with the SAS system using the programs available at CIMMYT (2004).

RESULTS AND DISCUSSION

There were significant differences among genotypes for biomass yield. The G x E interaction was not significant (Table 4). The highest biomass yield was for the genotypes Rojas, Tape, and Lucero. All of these genotypes are from Argentina, although the genotype Omega-USA did not differ significantly from the last three (Table 5). There were significant differences among genotypes for harvest index, the G x E interaction was not significant (Table 4). The genotype Rahab and Carapé had the highest harvest index of 37.7% (Table 5). This value is considered high for an oilseed crop which levels generally fluctuate between 20 and 30% (Aufhammer *et al*., 2000). Previous research has indicated that flax has higher harvest index than other oilseed with values approaching 40% (D'Antuono and Rossini, 1995). The 1000-seed weight was not different among genotypes and the G x E interaction was not

Table 4. Mean squares for biomass yield, harvest index, 1000-seed weight, test weight, and seed yield for 16 flax genotypes cultivated in 11 environments in South Central Chile.

Source of variation	df	Biomass yield	Harvest index	df	100-seed weight	Test weight	df	Seed yield
Environment (Env)	2	652	2	8	18	488	10	91 867 334
Rep(Env)	9	108	29	23	8	8	33	2 341 466
Genotype	15	22*	61*	15	10	26*	15	970 603
Genotype x Env	24	8	8	114	7	21*	144	823 248**
Error	111	12	7	321	8	7	471	368 110
CV, %		37	8		42	4		23

*Significant at $P \leq 0.05$.

Table 5. Mean biomass yield, harvest index, 1000-seedweight, and test weight of 16 flax genotypes across 11 environments in South Central Chile.

Genotype	Biomass yield[1]	Harvest index	100-seed weight[2]	Test weight
	t ha^{-1}	%	g	kg hL^{-1}
Carapé	7.8	37.7	6.1	68
Bison	8.3	31.1	6.2	69
Cathay	9.9	31.7	6.4	67
Linote	9.3	30.7	7.0	69
Lucero	11.7	35.5	5.9	67
Neche	8.9	30.5	6.0	68
Nekoma	9.0	29.2	7.9	69
Omega Argentina	8.4	33.8	6.3	68
Omega-USA	10.4	33.2	6.9	68
Pembina	9.8	34.2	5.9	69
Prompt	7.7	32.1	6.4	67
Rahab	9.2	37.6	8.9	69
Rojas	13.0	34.0	6.8	68
Salto	7.5	31.6	6.7	68
Tape	12.5	35.2	6.0	69
York	9.9	34.8	6.0	69
LSD (0.05)	2.7	2.7	1.3	2

[1]Mean values for biomass yield correspond to only three environments Chillán, Osorno, and Yungay, in 2003-2004.
[2]Mean values of 1000-seed weight and test weight correspond to nine environments, Chillán 2003-2004, Chillán 2004-2005 Fall and Spring seeded. Los Ángeles 2004-2005, Osorno 2003-2004 and 2005-2006, and Yungay 2003-2004 and 2004-2005.
LSD: least significant difference.

significant. Test weight was significantly different among genotypes and for the G x E interaction. The highest test weight was for the genotypes Rahab and Nekoma, although test weight can be genetically determined, environmental factors may affect seed filling and ultimately seed weight. Higher than optimum temperatures during seed filling or a severe defoliation may cause a decrease in seed weight (Cross *et al*., 2003). Of the 11 environments evaluated in this study, we did not observed diseases or insects that caused defoliation, and flowering occurred during the end of November through December when maximum temperatures were below 25 ºC at all environments. Flowering and seed filling was much later in Los Ángeles and Osorno than in Chillán, delaying harvest to February and even March. There was secondary and tertiary flowering on those environments with supplemental irrigation, Chillán and Los Ángeles.

The G x E interaction was significant for seed yield (Table 4). The environments with greater seed yield potential were Chillán 2003-2004 and Los Ángeles 2004-2005. The genotypes Cathay and Prompt had the highest seed yield in Chillán 2003-2004 with 5746 kg ha^{-1} and 5742 kg ha^{-1}, respectively (Table 6). Genotypes from Argentina had low seed yield the season 2003-2004 due lower stands. The Chillán and Los Ángeles environments had higher seed yield potential because they had supplemental irrigation during flowering and seed filling which promoted secondary and tertiary flowering. Lower seed yield was observed at the Chillán 2004-2005 spring planted environment and Chillán 2006-2007 where bird damage occurred before harvest. Bird damage occurred 2 wk before harvest, finches and pigeons fed on the mature bolls extracting the seeds. Since the G x E interaction was significant the data were analyzed with the AMMI and SREG models to determine the which-won-where for the genotypes and environments.

The AMMI and SREG analyses did not include the Argentinean genotypes, since there were not planted at all environments; however some of the Argentinean genotypes were as high yielding ($P < 0.05$) as Nekoma and York at Chillán 2003-2004, Los Ángeles 2004-2005, Osorno 2003-2004 and Osorno 2004-2005 (Table 6). Outstanding Argentinean genotypes were Salto, Tape, and Rojas. The Argentinean Omega genotype was always lower yielding at all environments. The general adaptation of Argentinean genotypes to South Central Chile was good and similar to that of North American genotypes.

Visualization of the genotype by environment interaction using the AMMI and SREG models

The information of seed yield contained in Table 6 is graphically displayed in an AMMI biplot (Figure 1). The environment main effect explained 76% of the total variation, the genotypes accounted for only 1% of the variation. The x-axis represents the main effect of genotypes and environments while the y-axis displays the interactions between the genotypes and the environment (Crossa *et al*., 1991) and reveals that 'Nekoma' interacted positively with the environments with positive PC1 scores ECHI0304, EOS0607, EOSO0304, EYU0405, ECHI0607, and ECHIPR04. There was little variation among the 10 genotypes in mean seed yield (Figure 1). Mean seed yield across genotypes was 2670 kg ha^{-1}.

The 11 environments were divided into four groups. Group 1 includes the environments ECHI0304 and ELA0405 which have the highest mean seed yield. These two environments were irrigated. Group 2 includes environments that were very close to the mean seed yield across all environments and with a PC1 near 0 such as EOS0607, EOSO0304, EYU0405, EYU0304, and EOS0405. The locations Osorno and Yungay are classified in the same agroclimate that may explain why they are

Table 6. Mean seed yield for 16 flax genotypes and 11 environments cultivated in South Central Chile.

Genotype	Chillán					Los Ángeles	Osorno			Yungay	
	2003/04	2004/05F[1]	2004/05S[2]	2005/06	2006/07	2004/05	2003/04	2004/05	2006/07	2003/04	2004/05
	kg ha^{-1}										
Carapé	2905	2285	702	3210	419	4255	2252	3137	2084	-	2629
Bison	4945	1023	1258	2347	735	4854	2874	3189	2214	3126	2392
Cathay	5746	1751	921	2412	620	3644	2773	3095	2499	3451	2545
Linott	5233	2275	738	2931	501	4086	2986	2779	2070	2799	2591
Lucero	3688	2485	603	3740	1055	4550	1855	2963	1958	-	2464
Neche	4084	1373	947	2007	526	4240	2933	2924	2241	2999	2225
Nekoma	5343	725	814	1909	684	4084	3902	2722	2837	2867	3124
Omega Argentina	3586	2563	513	3531	686	3554	2812	3094	2737	-	2342
Omega-USA	3969	2398	936	2768	415	3828	2962	2958	2210	3126	2608
Pembina	4566	2281	654	2410	587	4837	3326	3086	2046	3306	2591
Prompt	5742	1672	1168	1843	691	4585	3285	2799	2498	3216	2331
Rahab	4634	1639	1136	1934	457	4870	3283	3148	2333	3189	3106
Rojas	3737	2226	1249	3651	1204	4490	2631	2956	2413	-	2217
Salto	4786	2406	909	3187	1161	4448	2646	3196	2531	-	2549
Tape	4693	1602	923	1871	1174	4746	3189	2726	2349	-	2559
York	5210	2459	712	2609	563	5077	3756	3301	2969	3605	3489

[1]Fall planted.
[2]Spring planted.
LSD: least significant difference Genotype x Environment (0.05) = 840.

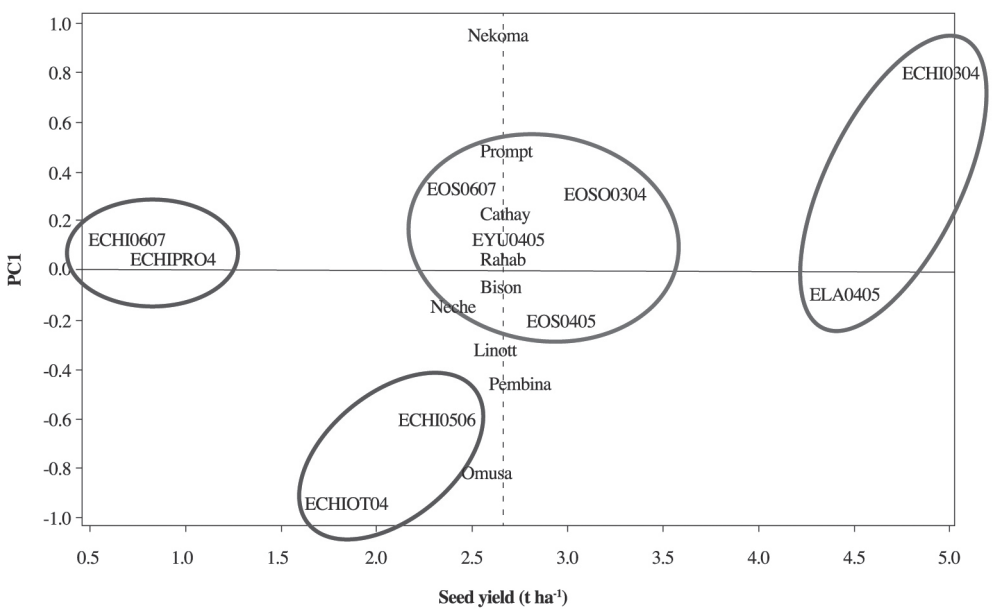

Figure 1. Biplot GE, AMMI model for 10 flax genotypes on 11 environments: Chillán 2003-2004 (ECHI0304), 2004-2005 Fall (ECHIOT04), 2004-2005 Spring (ECHIPR04), 2005-2006 (ECHI0506) and 2006-2007 (ECHI0607); Los Ángeles 2004-2005 (ELA0405), Osorno 2003-2004 (EOSO0304), 2004-2005 (EOS0405) and 2006-2007 (EOS0607); and Yungay 2003-2004 (EYU0304) and 2004-2005 (EYU0405). PC 1 = principal component 1. Dotted line indicates mean seed yield.

in the same group. Group 2 includes ECHI0506 and ECHIOT04 both average yielding environments, but with a negative interaction with the genotype Omega-USA, the lowest yielding genotype at those environments. Group 4 has the two lowest yielding environments ECHI0607 and ECHIPR04 both with the lowest mean seed yield. These two environments were seriously damage by birds before harvest that reduced seed yield. All genotypes were damaged similarly. Genotypes with a PC1 near 0 have a general adaptation to all the environments while those genotypes with PC1 positive or negative are adapted specifically to the environments with PC1 of the same sign either positive or negative (Romagosa and Fox, 1993) (Figure 1). 'Nekoma' and 'Prompt' were better adapted to ECH0304, EOS0304, and EOS0607 while 'Linott', 'Omega-USA', and 'Pembina' were better adapted to the environments in Group 3. The other genotypes Cathay, Rahab, Bison, Neche, and York have a general adaptation to all environments, i.e. they had a better yield stability (Diepenbrock *et al*., 1995).

The GGE biplot allowed us to evaluate the performance of the genotypes in each environment (Figure 2). The which-won-where pattern can be visualized only by the polygon view of a GGE biplot. The polygon is formed through connecting the markers of the four genotypes with the greatest seed yield response to the environments whether positive or negative. This indicates that 'Nekoma' had the highest seed yield followed by 'Cathay' and 'Rahab'. Oppositely, 'Omega-USA' was the genotype with the lowest seed yield. The ideal genotypes are those that have a high mean yield and a PC2 close to 0, or high stability. 'Nekoma' has both of these characteristics being the ideal genotype for this analysis. It is interesting to note that 'Nekoma' biomass yield and harvest index were not among the greatest values. This may indicate that greater biomass yield is not necessarily correlated with seed yield. The ideal environment is also the one with high seed yield and high stability. The only environment that was high seed yield was ECH0304 but its stability was low PC2 = 0.78. The 11 environments divided into three apparent groups in terms of their discrimination of the genotypes. Group 1 includes a single environment, ECHI0304 and Group 2 consists of ECHI0506 andECHIOT04. Group 1 and 2 were negatively correlated as evidenced by the large angle between them. As a result genotypes that yielded well in Group 1 would yield poorly in Group 2 and genotypes that yield well in Group 2 would yield poorly in Group 1.

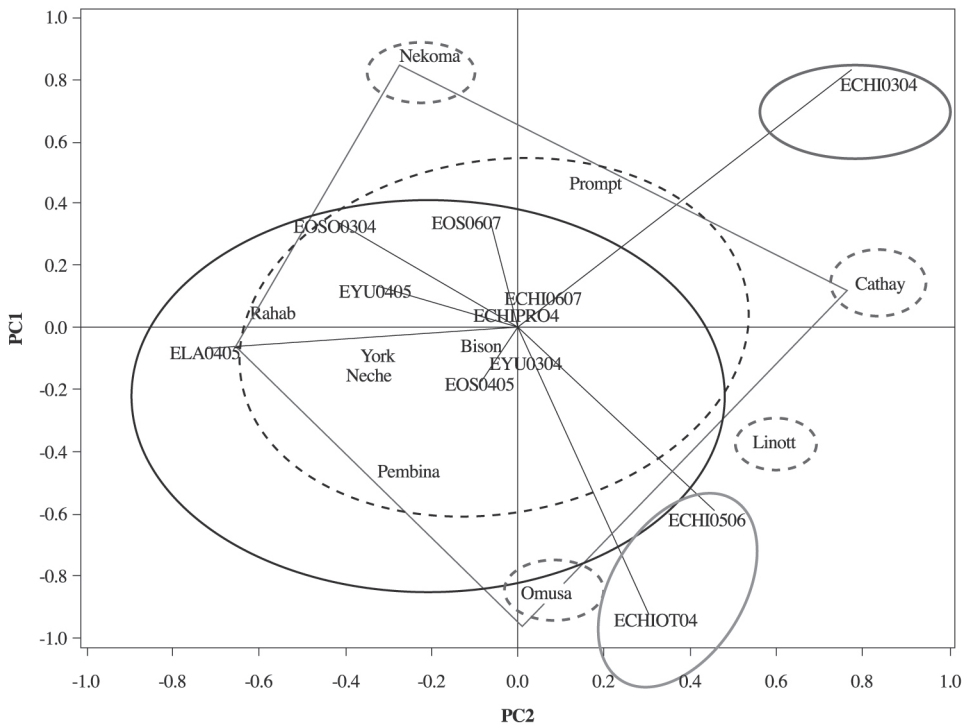

Figure 2. Biplot GGE for model SREG for 10 flax genotypes on 11 environments: Chillán 2003-2004 (ECHI0304), 2004-2005 Fall (ECHIOT04), 2004-2005 Spring (ECHIPR04), 2005-2006 (ECHI0506) and 2006-2007 (ECHI0607); Los Ángeles 2004-2005 (ELA0405), Osorno 2003-2004 (EOSO0304), 2004-2005 (EOS0405) and 2006-2007 (EOS0607), and Yungay 2003-2004 (EYU0304), and 2004-2005 (EYU0405). PC1= Principal component 1; PC2 = Principal component 2. Full-line ovals indicate the groups of environments (3) and dashed-line ovals the groups of genotypes (5).

Group 3 includes all the other environments and is located near the origin indicating that this group of environments was not discriminating of the genotypes, i.e. all genotypes had similar seed yield in those environments. The GGE biplot revealed five apparent groups of genotypes in terms of their response to the environments (Figure 2). The first four groups included single genotypes, Nekoma, Cathay, Linott, and Omega-USA. Group 5 consisted of all the other genotypes evaluated.

There was a significant difference for the genotype and G x E interaction for oil content (Table 7). The oil content was lower at Chillán and Osorno in 2006-2007 and the highest oil content was for Chillán 2003-2004, Chillán 2004-2005 spring-planted and Yungay 2003-2004 (Table 7). Environmental conditions such as temperature during seed development, N deficiency, and water availability influence the oil content of flax seed (Adugna and Labuschagne, 2003).

All fatty acid profiles evaluated were different among genotypes. The G x E interaction was significant only for oleic acid (Table 8). Alpha linolenic acid is the most import fatty acid in flax seed. All genotypes had more than 54% of linolenic acid. The genotypes Neche and Nekoma were among the genotypes with highest linolenic acid content. Environmental differences were not significant for fatty acid composition.

CONCLUSIONS

Flaxseed adapts to South Central Chile although differences were observed among genotypes for biomass yield, harvest index, test weight, and oil content and composition. Seed yield was above 5700 kg ha^{-1} for some environments and genotypes, indicating the high seed yield potential of some environments in South Central Chile. According to the AMMI and SREG models the 11 environments were classified into four groups by the AMMI and three groups by the SREG models. Genotypes were classified in five groups in the SREG model; four of those groups were single genotypes. Overall mean seed yield was similar for all genotypes; however the genotype Nekoma was the most stable and higher yielding genotype of the North American genotypes evaluated. The environment with highest yielding potential was Chillán 2003-2004, but had low stability.

The greatest oil contents were observed at the Chillán 2003-2004, 2004-2005 Spring sown, and Yungay 2003-2004 environments, and fluctuated between 420 and 530 g kg^{-1}.The climatic differences among environments did not influence oil composition as was expected based on previous research. Flax could become an excellent alternative for crop rotation in South Central Chile given its great seed yield potential.

Table 7. Mean seed oil content for 16 flax genotypes and 11 environments cultivated in South Central Chile.

	Chillán					Los Ángeles	Osorno			Yungay	
Genotype	2003/ 2004	2004/ 2005F[1]	2004/ 2005S[2]	2005/ 2006	2006/ 2007	2004/ 2005	2003/ 2004	2004/ 2005	2006/ 2007	2003/ 2004	2004/ 2005
	%										
Carapé	42.7	44.9	43.9	43.9	36.9	42.5	43.8	44.1	34.6	-	43.6
Bison	45.3	42.6	48.9	43.0	37.6	42.3	44.8	42.7	33.9	46.7	41.6
Cathay	49.6	43.9	49.8	43.8	37.7	42.8	50.5	43.0	33.0	46.9	42.5
Linott	51.7	44.0	50.1	43.2	35.6	42.1	49.3	43.2	34.0	54.0	43.9
Lucero	48.3	43.3	51.2	42.8	31.5	42.9	45.8	42.9	33.0	-	42.2
Neche	50.2	43.5	49.7	43.0	31.8	42.2	47.3	42.9	33.9	49.7	42.4
Nekoma	49.9	43.3	50.2	42.9	32.7	42.3	46.6	43.1	32.5	48.7	43.0
Omega Argentina	45.8	43.8	49.4	42.3	33.3	42.0	47.7	42.2	32.9	-	41.0
Omega-USA	46.3	45.3	50.9	44.4	37.3	42.5	45.5	44.4	34.0	53.4	43.5
Pembina	48.8	45.0	50.4	43.9	35.5	42.5	47.9	43.6	35.1	50.1	43.2
Prompt	46.9	42.8	48.5	42.8	37.1	42.3	44.0	42.3	31.6	42.8	41.9
Rahab	49.7	43.3	47.7	43.7	34.1	41.9	43.8	42.8	33.7	53.2	43.0
Rojas	51.8	43.8	48.4	42.3	36.6	43.7	43.3	41.4	34.1	-	42.2
Salto	53.4	44.7	47.7	43.0	36.7	41.4	42.0	42.4	34.6	-	42.6
Tape	47.2	43.5	48.5	42.8	32.4	41.2	42.5	41.6	34.6	-	41.7
York	43.0	43.1	48.5	42.5	38.2	42.0	45.9	42.1	34.0	50.6	41.8

[1]Fall planted.
[2]Spring planted.
LSD: least significant difference Genotype x Env (0.05) = 2.6.

Table 8. Mean seed oil content and fatty acid composition for 16 flax genotypes across 11 environments.

Genotype	Oil content	Palmitic	Stearic	Fatty acids		
				Oleic	Linoleic	Linolenic
	%					
Carapé	42.2	5.7	4.3	15.3	15.6	57.2
Bison	42.1	5.4	3.7	16.5	16.4	56.2
Cathay	43.2	5.0	3.7	15.6	17.8	56.3
Linott	43.8	5.0	3.6	15.5	17.0	57.6
Lucero	41.4	5.9	4.9	16.3	15.2	55.8
Neche	42.5	4.9	3.6	14.7	16.2	59.1
Nekoma	42.7	4.8	3.6	14.3	16.7	59.5
Omega Argentina	41.9	4.8	3.5	17.0	17.2	56.4
Omega-USA	43.0	6.0	5.0	16.0	16.3	54.6
Pembina	43.5	4.9	3.8	15.9	18.6	55.7
Prompt	42.0	5.0	3.2	15.8	16.0	58.6
Rahab	43.0	5.0	4.1	15.9	18.0	55.4
Rojas	42.4	5.8	4.8	14.2	16.0	57.0
Salto	42.3	6.0	4.6	14.3	18.2	54.0
Tape	41.0	5.9	4.5	15.2	15.3	57.0
York	42.3	5.0	3.8	15.4	16.0	57.7
LSD (0.05)	1.4	0.2	0.6	0.7	0.7	1.4

LSD: least significant difference.

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RESUMEN

Adaptación e interacción genotipo x ambiente en lino (*Linum usitatissimum* L.) en la zona centro sur de Chile. La semilla de lino (*Linum usitatissimum* L.) se importa a Chile principalmente para panaderías y alimento animal. La identificación de genotipos altamente productivos en la zona Centro Sur de Chile facilitaría la decisión de los productores. El objetivo de este estudio fue determinar la adaptación y la interacción genotipo x ambiente de 16 genotipos de lino (incluyendo 10 procedentes de Norte América y 6 de Argentina) los que se sembraron en 11 ambientes (localidad-año) en Chile entre el 2003 y el 2007. El rendimiento de semillas observado fue de más de 5700 kg ha^{-1} en algunos ambientes lo que indicaría un alto potencial. De acuerdo a los modelos AMMI y SREG los 11 ambientes fueron clasificados en cuatro grupos por el modelo AMMI y en tres grupos por el modelo SREG. Los genotipos fueron clasificados en cinco grupos por el modelo SREG, donde cuatro de los grupos incluían un sólo genotipo. El promedio general de rendimiento de semillas fue similar para todos los genotipos, sin embargo, el genotipo Nekoma fue considerado el más estable y de mayor rendimiento de semillas en todos los ambientes evaluados. El ambiente con mayor rendimiento fue Chillán 2003-2004, pero esta localidad tuvo baja estabilidad en el tiempo. Los ambientes con más alto rendimiento fueron Chillán 2003-2004 y Los Ángeles 2004-2005, hay que considerar que ambos ambientes fueron regados durante floración y llenado de granos. El contenido de aceite fluctuó entre 420 y 530 g kg^{-1}. Las diferencias climáticas entre ambientes no influenciaron la composición del aceite como se esperaba. El lino se adapta a la zona centro sur de Chile observándose diferencias entre genotipos para rendimiento de biomasa y semillas, índice de cosecha, peso del hectolitro, contenido y composición del aceite.

Palabras clave: Adaptación, genotipo, producción de semilla, contenido de aceite, ácido linolénico, *Linum usitatissimum*.

LITERATURE CITED

Ackman, R.G. 2002. The gas chromatograph in practical analyses of common and uncommon fatty acids for the 21st century. Analytica Chimica Acta 465:175-192.

Adugna, W., and M.T. Labuschagne. 2003. Association of linseed characters and its variability in different environments. Journal of Agricultural Science 140:285-296.

Aufhammer, W., W. Wagner, H.P. Kaul, and E. Kubler. 2000. Radiation use by oil seed crops-a comparison of winter rape, linseed, and sunflower. Journal of Agronomy and Crop Science 184:277-286.

Berglund, D., and R. Zollinger. 2002. Flax production in North Dakota. Bull. A-1038. 12 p. North Dakota Agricultural Experimental Station, Extension Service North Dakota, Fargo, North Dakota, USA.

Carrasco, P. 1998. Descripciones de Suelos VIII Región. 80 p. Universidad de Concepción, Facultad de Agronomía, Departamento de Suelos, Chillán, Chile.

Casa, R., G. Russell, B. Lo Cascio, and F. Rossini. 1999. Environmental effects on linseed (*Linum usitatissimum* L.) yield and growth of flax at different stand densities. European Journal of Agronomy 11:267-278.

Charlton, B., and D. Ehrensing. 2001. Fiber and oilseed flax performance annual report. Oregon State University, Corvallis, Oregon, USA.

CIMMYT. 2004. Biometrics and Statistics Unit. Manuals and programs. CIMMYT. [Online] Available at http://www.cimmyt.org/en/about-us/organizational-structure/units-a-labs/crop-research-informatics-laboratory/disciplinary-groups-units/biometrics-and-statistics-unit (accessed September 2010).

Cross, R.H., S.A.B. McKay, A.G. McHughen, and P.C. Bonham-Smith. 2003. Heat-stress effects on reproduction and seed set on *Linum usitatissimum* L. (flax). Plant Cell and Environment 26:1013-1020.

Crossa, J., and P.L. Cornelius. 1997. Sites regression and shifted multiplicative model clustering of cultivar trials sites under heterogeneity of error variances. Crop Science 37:406-415.

Crossa, J., P.N. Fox, W.H. Pfeiffer, S. Rajaram, and H.G. Gauch, Jr. 1991. AMMI adjustment for statistical analysis of an international wheat yield trial. Theoretical and Applied Genetics 81:27-37.

D'Antuono, L.F., and F. Rossini. 1995. Experimental estimation of linseed (*Linum usitatissimum* L.) crop parameters. Industrial Crops and Products 3:261-271.

Del Pozo, A., y P. Del Canto. 1999. Áreas agroclimáticas y sistemas productivos en la VI y VIII Regiones. Serie Quilamapu Nº 113. Instituto de Investigaciones Agropecuarias, Centro Regional de Investigación Quilamapu, Chillán, Chile.

DIMEAGRO. 2007. Perfil del mercado del lino 2006. [Online] Gacetilla Informativa del sector agroalimentario. Secretaría de Agricultura, Ganadería, Pesca y Alimentos, República Argentina. Available at http://www.sagpya.mecon.gov.ar/new/0-0/programas/dma/newsletters/nro25/newsletter_lino-01-12-2006.php (accessed January 2008).

Diepenbrock, W.A., J. León, and K. Clasen. 1995. Yielding ability and yield stability of linseed in Central Europe. Agronomy Journal 87:84-88.

Dybing, C.D., P.D. Evenson, and C. Lay. 1988. Relationships among daily flower production, length of the flowering period, and seed yield of flax. Crop Science 28:287-292.

FAO. 2009. FAOSTAT database. Agricultural crops: linseed: area harvested/yield. Available at http://faostat.fao.org/ (accessed September 2010).

Froment, M.A., J. Smith, and K. Freeman. 1999. Influence of environmental and agronomic factors contributing to increased levels of phospholipids in oil from UK linseed *Linum usitatissimum*. Industrial Crops and Products 10:201-207.

Grady, K., and L. Gilbertson. 2009. South Dakota flax variety evaluations 2009. Bull. ExEx8055. October 2009. Cooperative Extension Service South Dakota State Univ. Brookings, SD.

Grady, K.A., and C.L. Lay. 1994. Registration of "Prompt" Flax. Crop Science 34:308.

Grady, K.A., C.L. Lay, and M.W. Ferguson. 1987. Registration of 'Rahab' flax. Crop Science 27:362-363.

Hammond, J.J., J.F. Miller, G.D. Statler, and T.J. Gulya. 1991. Registration of "Neche" Flax. Crop Science 31:847.

Kempton, R.A. 1984. The use of biplots in interpreting variety by environment interactions. Journal of Agricultural Science 103:123-135.

Ma, B.L., W. Yan, L.M. Dwyer, J. Frégeau-Reid, H.D. Voldeng, Y. Dion, and H. Nass. 2004. Graphic analysis of genotype, environment, nitrogen fertilizer, and their interactions on spring wheat yield. Agronomy Journal 96:169-180.

Madhusudhan, K.T, H.P. Ramesh, T. Ogawa, K. Sasaoka, and N. Singh. 1986. Detoxification of commercial linseed meal for use in broiler rations. Poultry Science 65:164-171.

Miller, J.F., J.J. Hammond, and G.D. Statler. 1988. Registration of four flax germplasm lines. Crop Science 28:579.

Miller, J.F., J.J. Hammond, and G.D. Statler. 1992. Registration of 'Omega' flax .Crop Science 32:1065.

Novoa, R., S. Villaseca, P. del Canto, J. Rouanet, C. Sierra, y A. Del Pozo. 1989. Mapa agroclimático de Chile. Instituto de Investigaciones Agropecuarias (INIA), Santiago, Chile.

Oomah, B.D., E. Kenaschuk, and G. Mazza. 1996. Phytic acid content of flaxseed as influenced by cultivar, growing season, and location. Journal of Agricultural and Food Chemistry 44:2663-2666.

Romagosa, I., and P.N. Fox. 1993. Genotype x environment interaction and adaptation. p. 374-390. *In* Hayward, M.D., N.O. Bosemark, and I. Romagosa (eds.) Plant breeding, principles and prospects. Chapman & Hall, London, UK.

SAS Institute. 2007. SAS/STAT® User's guide, Version 9.1. 4th ed. Vol. 1. SAS Institute, Cary, North Carolina, USA.

Steel, R.G.D., J.H. Torrie, and D.A. Dickey. 1996. Principles and procedures of statistics: A biometrical approach. 3nd ed. McGraw-Hill, New York, USA.

Vargas, M., y J. Crossa. 2000. El análisis AMMI y la gráfica del biplot en SAS. Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), México D.F., México.

Yan, W. 2001. GGEBiplot- A Windows applications for graphical analysis of multi-environment trial data and other types of two way data. Agronomy Journal 93:1111-1118.

Yan, W. 2002. Singular-value partition for biplot analysis of multi-environment trial data. Agronomy Journal 94:990-996.

Yan, W., L.A. Hunt, Q. Sheng, and Z. Szlavnics. 2000. Cultivar evaluation and mega-environment investigation based on the GGE biplot. Crop Science 40:597-605.

Yan, W., M.S. Kang, B. Ma, S. Woods, and P.L. Cornelius. 2007. GGE Biplot vs. AMMI analysis of genotype-by-environment data. Crop Science 47:643-653.

Zobel, R.W., M.J. Wright, and H.G. Gauch. 1988. Statistical analysis of a yield trial. Agronomy Journal 80:388-393.