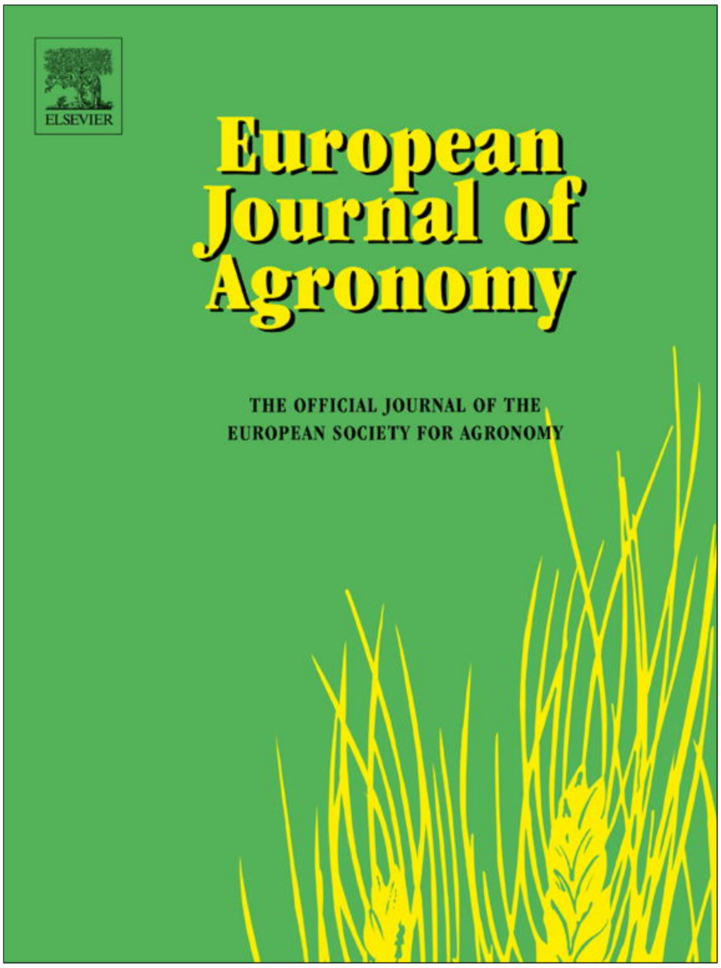

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Environmental factors affecting yield variability in spring and winter rapeseed genotypes cultivated in the southeastern Argentine Pampas

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ABSTRACT

Rapeseed yields in Argentina are low (averaging 1400 kg/ha nationwide) with a high inter-annual variability. One of the limiting factors for improving yields is the lack of information on the adaptability of the cultivars, especially in the main rapeseed-producing area, the southeastern Pampas. The objectives of this study were to (i) quantify and analyze the yield variability of winter and spring rapeseed hybrids introduced in Argentina, (ii) identify the main environmental factors that affect the yields of the spring and winter genotypes in the southeastern Pampas, and (iii) model and validate rapeseed yields from environmental variables in the pre- and post-flowering periods. Principal component analysis (PCA) and linear regression methods were used to analyze 129 data points from 16 comparative yield trials in eight sites of southeastern Pampas. The rainfed crops were sown between April and July and from 2007 to 2009. Pre- and post-flowering phases were recorded in each experiment; temperature, frost occurrences, rainfall and radiation were measured during each phase. Yield variability (600–3700 kg ha^{-1}) was slightly lower in spring than in winter genotypes (CV 0.25 versus 0.38). Sixty percent of the winter genotype variability was explained by the first axis which was associated to the pre- and post-flowering durations, while 25% of the variability was explained by the second axis associated to yield. Almost 50% of the spring genotype variability was explained by the first axis associated to pre-flowering and total durations, while 27% of the variability was explained by the second axis in which post-flowering duration was associated to yield. Winter genotypes evidenced vernalization requirements that were either partially or not fulfilled, so, the longer the photoperiod, the longer the pre-flowering phase duration. In the critical period of 30 d post-flowering, yield was not associated to the photothermal quotient. In winter genotypes, yield was associated to a linear model which included rainfall during the crop cycle, radiation and pre-flowering temperatures ($R^2 = 0.50$). The model was adequately validated with independent data ($n = 116$) from official trials. For spring genotypes, only the frost occurrences during the critical period were relevant ($R^2 = 0.26$) and placing the flowering time after October decreased the risk of late frost damage. Water use efficiency (WUE) values ranged from 1.6 to 6.7 kg ha^{-1} per mm of rain without a clear trend between spring and winter genotypes for this trait. In conclusion, winter genotypes did not necessarily yield more than the spring materials. In addition, rainfall during the crop cycle and frost occurrences during flowering were the main limiting factors of the winter and spring genotype yields, respectively, in the southeastern Pampas.

1. Introduction

Rapeseed (*Brassica napus* L.) is the third most important oilseed in the world, following palm and soybeans (Oil World, 2012). Its cultivation in Argentina began in the 1930s and has been fluctuating around 39,000 has, a small area compared to other countries such as Canada, China, India, Germany, Australia or France (Rondanini et al., 2012). However, in the last ten years rapeseed has drawn a renewed interest in the Argentinean farmers due to economical and agronomical factors. Among the economical factors are the biofuel boom and the possibility of supplying the oil industry during inactive periods, while the agronomic factors include the possibility of replacing winter cereals with winter oilseed in the rotations, the incorporation of carbon into the soil due to the great amount of crop

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residues, and the possibility of anticipating harvest (before wheat and barley) that would lead to an earlier planting of double-crop soybeans.

Argentinean climatic conditions are adequate for both winter and spring rapeseed cultivation, which differ in the vernalization requirements (i.e., hours with temperatures <5–8 °C) for flowering (Murphy and Pascale, 1990). The areas where rapeseed cultivation has expanded most coincide with the wheat-growing areas, especially in the central-south region of Buenos Aires province which produces 65% of the national rapeseed production. Although the national rapeseed yield averaged 1400 kg ha^{-1} in the last decade, potential yields in experimental plots have ranged from 4000 to 7000 kg ha^{-1} (Iriarte and Valetti, 2008; Gomez and Miralles, 2011), indicating an important gap between actual and potential yields. As a general rule, rapeseed yields are expected to reach 40–50% of wheat yields (Holland et al., 1999), however, in low potential environments, rapeseed and wheat yields may match (Rondanini et al., 2012). Nonetheless, producers in the southeastern Pampas perceive rapeseed as a risky crop due to the high yield variability among locations and years.

A wide offer of genotypes (varieties and hybrids) is currently available in the market for both winter and spring rapeseed as commercial genotypes from diverse origins (Canadian, German, Polish, Indian, Australian and French) have been introduced and tested by seed companies in the last ten years. Recently winter French genotypes have been introduced in Argentina with the expectation to improve yield as those materials have a longer cycle duration and therefore accumulate more biomass, so it is assumed that they could have a greater yield potential compared to spring genotypes (Diepenbrock, 2000; Berry and Spink, 2006). However, that speculation has not been tested experimentally in the Argentinean environments.

Environmental factors that affect yield include temperature, radiation, photoperiod, frost occurrences and water availability. The impact of these factors on yields of rapeseed genotypes has been evaluated in productive environments of Canada, Australia, Finland and the UK (e.g., Kutcher et al., 2010; Lisson et al., 2007; Peltonen-Sainio and Jauhiainen, 2008; Berry and Spink, 2006) but has not yet to be studied in productive areas of the southeastern Pampas. The different photoperiod response and vernalization requirements of the genotypes (e.g. between spring and winter oilseed rape types) determine differences in the length of the phases exposing the crop to different environments, especially during the critical period and thereby affecting yield (Miralles et al., 2001). Also, one of the most important points in terms of yield generation, independent of the cycle length, is associated with the environmental conditions occurring during the critical period of flowering and seed setting. In winter rapeseed genotypes it comprises 350 °Cd (Habekotté, 1997) or 4 weeks (Mingeau, 1974) after the start of flowering. The photothermal quotient (relation between radiation and temperature) during the critical period around flowering has shown an association with the yields of various crops in the Pampas region, like wheat, maize and sunflower (see references in Hall et al., 1992; and Sadras and Calderini, 2009). Until now, this relationship has not been tested for rapeseed. On the other side, photothermal quotient fit well with yield under non water restrictions. However, excessive or insufficient rainfall affects the foliar expansion and light interception (Mendham and Salisbury, 1995), reducing the crop water use efficiency which ranges from 14 to 4 kg ha^{-1} mm^{-1} according to the genotype and the environment (Taylor et al., 1991; Grey, 1998; Robertson and Holland, 2004).

Appropriate management practices (e.g. sowing dates) aimed to maximize the performance of winter and spring rapeseed genotypes could be defined by relating yields to particular environmental conditions. Therefore, the objectives of this study were to (i) quantify and analyze the yield variability of winter and spring rapeseed hybrids introduced in Argentina, (ii) identify the main environmental factors that affect the yields of the genotypes in the southeastern Pampas, and (iii) model and validate rapeseed yields from environmental variables in pre- and post-flowering.

Table 1
Detail of French winter rapeseed genotypes (FWG), winter commercial genotypes (CWG) and spring commercial genotypes (CSG) evaluated during three years (2007–2009) in eight locations of the southeastern Pampas.

Group	Code[a]	Name	Type	Company
FWG	01	HSP3	Hybrid	Syngenta
	02	HBB2	Hybrid	Syngenta
	03	HT1	Hybrid	Syngenta
	04	HPTR4	Hybrid	Syngenta
	05	HSE5	Hybrid	Syngenta
	06	HOT6	Hybrid	Syngenta
	07	HKR7	Hybrid	Syngenta
	08	HRY8	Hybrid	Syngenta
CWG	09	Gospel	Variety	Sursem
	12	SW 2586	Variety	Sursem
	14	Barrel	Variety	Al High Tech
	15	Sitro	Hybrid	Al High Tech
	16	Pulsar	Hybrid	Al High Tech
	17	Hornet	Hybrid	Al High Tech
	18	Teddy	Variety	Al High Tech
CSG	10	Sursem 2836	Variety	Sursem
	11	SW 2797	Hybrid	Sursem
	13	Foremost	Variety	Al High Tech
	19	Hyola 61	Hybrid	Advanta
	20	Hyola 432	Hybrid	Advanta
	21	Nexera	Variety	DOW

[a] Genotype codes used in the PCA.

2. Materials and methods

2.1. Field experiments

Eight French winter-type (FWG), seven commercial winter-type (CWG) and six commercial spring-type genotypes (CSG) were tested (Table 1). Sixteen comparative yield trials were conducted on commercial farms during three years (2007, 2008 and 2009) in eight sites (Balcarce, Tandil, Chillar, Tres Arroyos, San Cayetano, Gonzales Chaves, Barrow and Daireaux) that cover a vast wheat-growing area of central-south Buenos Aires province, Argentina, located between 36°34′ and 38°33′S latitude and between 58°18′ and 61°54′W longitude. The soils in Balcarce, Necochea, Tandil and Chillar have textures that range from silty clay loams to sandy loams. Soil subgroups in these sites included typic argiudolls, typic shallow argiudolls and petrocalcic paleudolls. The average topsoil organic matter ranges from 4 to 6% while the soil depth reaches from 0.7 to 2 m; available water holding capacity averages 1.5 mm cm^{-1} soil (Travasso and Suero, 1994; Sadras and Calviño, 2001; Calviño et al., 2003). In Daireaux, sandy loam textures predominate with 2–3% organic matter, good to excessive drainage without soil restrictions and a deep water table (>2 m) and a moderate to strong wind erosion (Santanatoglia et al., 2005; GeoINTA, 2012). Cropping rotations in the area include wheat and wheat/soybean double cropping, all under conservation tillage practices. The genotypes were sown in experimental plots of 6 m long and 2 m wide and the genotypes varied among sites and years (Table 2). Sowing was carried out under direct drill on plots with stubble from previous wheat crops. Sowing dates varied greatly among years and sites (Table 2). Experiment E1 was sown very late (5-Jul-07) due to a delay in seed importation, while the rest of the trials were sown early (March–April), or at the recommended time for sowing (May–June) depending on the site. Planting density ranged from 3 to 5 kg seed per ha,

Table 2
Detailed list of the rapeseed comparative yield trials conducted during three years (2007–2009) in eight locations of the southeastern Pampas.

Experiment	Year	Site	Sowing date	Code of evaluated genotypes[a]	Total evaluated genotypes
E1	2007	Balcarce	5-Jul-07	1–3, 9–11, 13–14, 16, 21	10
E2	2008	Balcarce	29-Apr-08	1–3, 6, 9–11, 15–16, 18, 20	11
E3	2008	Balcarce	6-Jun-08	1–8, 9–11, 15–18, 20	16
E4	2008	Chillar	25-Apr-08	1–3, 9–11, 15–18, 20	11
E5	2008	Chillar	14-Jul-08	1–8, 9–11, 15–17, 20	15
E6	2008	Tres Arroyos	11-Jun-08	1–8, 9–11, 20	12
E7	2009	San Cayetano	18-May-09	2–4, 10, 18	6
E8	2009	G. Chaves	26-Mar-09	2–4, 18	4
E9	2009	Daireaux	17-Mar-09	2–4, 11	4
E10	2009	Chillar	20-Mar-09	2–4, 9, 12	5
E11	2009	Tandil	23-Mar-09	2–4, 9	4
E12	2009	Tandil	4-Apr-09	2–4, 9, 16	5
E13	2009	Tandil	14-Apr-09	2–4, 19–21	6
E14	2009	Balcarce	30-Apr-09	2–4, 6, 9, 10, 19	7
E15	2009	Balcarce	7-Apr-09	2–4, 6, 10, 18, 20	7
E16	2009	Barrow	21-Apr-09	2–4, 6, 9, 21	6

[a] Refer to Table 1 for genotype codes.

rows distance was between 0.2 and 0.35 m, N and S fertilization at sowing (80–100 kg N ha^{-1} and 10–15 kg S ha^{-1}), and chemical control of insects and weeds. The experiments, described in detail in Table 2, were part of the cultivar-testing program of Syngenta Agro S.A. Company.

2.2. Recorded and analyzed variables

The recorded variables included sowing date, flowering date when 50% of the plants into the plots had an open flower, harvest date, and the duration of the complete cycle (days from sowing to harvest, "dursh") which was divided into the stages of pre-flowering (between sowing and flowering, "dursf") and post-flowering (flowering to harvest, "durfh"). The time of harvest was not necessarily associated with physiological maturity as this attribute was not recorded due to the difficulty in determining its exact moment with visual methods. Grain yield (kg ha^{-1}) was determined by harvesting three to four central rows in each plot. Yield data was presented with 8% moisture. Local mean daily temperature and daily global incident radiation was obtained from the Climate and Water Institute (INTA) data base; rainfall (mm) was recorded at each experiment site. Mean average temperature (°C), accumulated incident radiation (MJ m^{-2}), and accumulated precipitations (mm) were calculated for sowing-flowering (sf) and flowering-harvest (fh) period, so those variables were named: tempsf, tempfh, radsf, radfh, rainsf, and rainfh, respectively. Also, frost occurrence (minimum daily temperature $< 0\,°C$) were recorded for the critical period of 0–30 d after flowering (frost cp). Critical period varies according to different authors – four weeks after flowering, according to Mingeau (1974) dealing with winter genotypes exposed to different drought periods; Mendham et al. (1981) dealing with field-grown winter genotypes reported the critical period two weeks after flowering; or 350 °Cd (base temperature 0 °C) from the beginning of flowering as was reported by Habekotté (1997) which is equivalent to approximately 30–40 d immediately after flowering applying the crop simulation model 'Lintul-Brasnap' for winter genotypes. This early reproductive stage coincides with flowering and fruit set of pods, both in the main raceme and floral branches, being key processes for the definition of rapeseed grain yield (Diepenbrock, 2000; Berry and Spink, 2006). Based on these findings from the literature, a range of 0–30 d post-flowering was assumed as the critical period for winter and spring genotypes in the present work. The photothermal quotient (MJ m^{-2} d^{-1} $°C^{-1}$) was calculated as the ratio between the daily incident global solar radiation (MJ m^{-2} d^{-1}) and the mean average temperature (°C) during the critical period of 0–30 d after flowering. Precipitations during two fallow periods were determined, a short one where the accumulated precipitations 30 d before sowing, and a long fallow period where the accumulated precipitations for a period of 60 d before sowing were considered.

2.3. Data analysis

Descriptive statistics and box-plots were used to analyze the variables in each group of genotypes (FWG, CWG, CSG). Values in the text are mean ± 1 SD except if indicated otherwise. A principal component analysis (PCA) was conducted on a data matrix with rows containing the combination of genotype, year, site and sowing dates ($n = 129$), and columns containing the four observed response variables: yield, total crop cycle duration in days from sowing to harvest (dursc), days from sowing to flowering (dursf) and days from flowering to harvest (durfc). The objective of this analysis was to explain the wide variability observed in the data by exploring the main sources of this variability (axes ordering). Visualization of the principal components on each axis and their relationship with the vectors (response variables) was possible with graphical representations (biplots) developed from the first and second order axes according to the methodology proposed by DeLacy et al. (1996) and de la Vega and Chapman (2006). Similar principal component analysis was performed to cases from winter ($n = 99$) and spring ($n = 30$) genotypes. Each case was identified with a code; the first letter representing the origin of the plant material (F: French, C: Commercial), the second letter the growing habit (W: Winter, S: Spring), the third letter the site (B: Balcarce; C: Chillar, T: Tres Arroyos, S: San Cayetano, G: González Chaves, D: Daireaux, L: Tandil), the fourth to fifth places representing the genotype code (see Table 1), the penultimate place corresponding to the month of sowing (from 3: March to 7: July), and the last place representing the year of evaluation. For example, the code – FWB0449 represents a French and winter genotype, sown in Balcarce, genotype coded as 04 (named HPTR4), sown in April (4th month of year) of 2009. A multivariate analysis was performed with the PC-ORD program (Multivariate Analysis of Ecological Data, v5, JMJ Software). After ordering of axes, correlations were performed between the principal components (axes 1 and 2) and the following environmental variables in the pre- and post-flowering stages: average photoperiod, accumulated precipitations, average mean temperature and accumulated incident global solar radiation. The relationship between yield and the photothermal ratio was analyzed by simple linear regression. A linear regression model relating yield to total rainfall during the crop cycle (i.e. from sowing to harvest) was adjusted with the 10, 50 and 90th quantile of the yield distribution (Koenker and Basset, 1978) using the BLOSSOM Statistical Package Version W2001.08d (Midcontinent Ecological Science Center: US Geological Survey). The slope of the 90th quantile line represents the highest water use efficiency (WUE) threshold and indicates the crop response in the years when the seasonal conditions are given for maximum water use efficiency. Multiple linear regression models were adjusted to determine if a linear combination of environmental variables was useful to explain the yield variability observed across sites and years. A separate model was adjusted for spring and winter genotypes due to their different characteristics. An alpha value of 0.05 was chosen to enter variables in the model. Independent data ($n = 143$) to validate the selected models were obtained from official comparative yield trials (CYTs) conducted by the Instituto Nacional de Tecnologia Agropecuaria of Argentina (INTA) from 2007 to 2010 (Ross, 2007; Iriarte et al., 2007, 2008; Iriarte and Lopez, 2010; PNEG, 2011). Trials were conducted under rainfed field conditions in Barrow and Balcarce, exhibiting yield ranges of 780–4100 and 750–3450 kg ha^{-1} for winter ($n = 48$) and spring genotypes ($n = 95$), respectively. Winter genotypes included FWG ($n = 17$) and CWG ($n = 31$). Further details about these experiments are shown in Supplementary material. Meteorological data was obtained from the Climate and Water Institute and Barrow Station (INTA) and were used to calculate predicted yield values. Prediction quality of the relationships was evaluated using the hypothesis of intercept = 0 and slope = 1 for the regressions between observed and estimated data ($p < 0.05$).

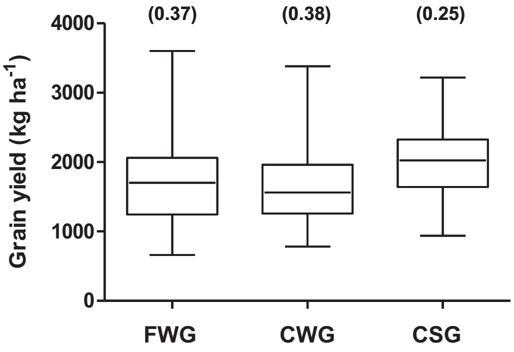

Fig. 1. Rapeseed grain yield box-plots representing the data distribution of French winter genotypes (FWG), commercial winter genotypes (CWG), and commercial spring genotypes (CSG) evaluated during three years (2007–2009) in eight locations of the southeastern Pampas. Numbers between brackets show the coefficient of variation.

3. Results

3.1. Yield and crop cycle duration in genotype groups FWG, CWG and CSG

Grain yield varied widely across all groups of genotypes in the three years and eight sites of the southeastern Pampas region (Fig. 1). Average yields by site ranged from 1600 to 2000 kg ha^{-1}, while the average yields by year varied from 1200 to 1800 kg ha^{-1} (2007), 700 to 2500 kg ha^{-1} (2008) and from 600 to 3700 kg ha^{-1} (2009). French winter genotypes (FWG) yields averaged 1755 ± 658 kg ha^{-1} and ranged from 660 to 3600 kg ha^{-1}. Yields of commercial winter genotypes (CWG) also varied widely,

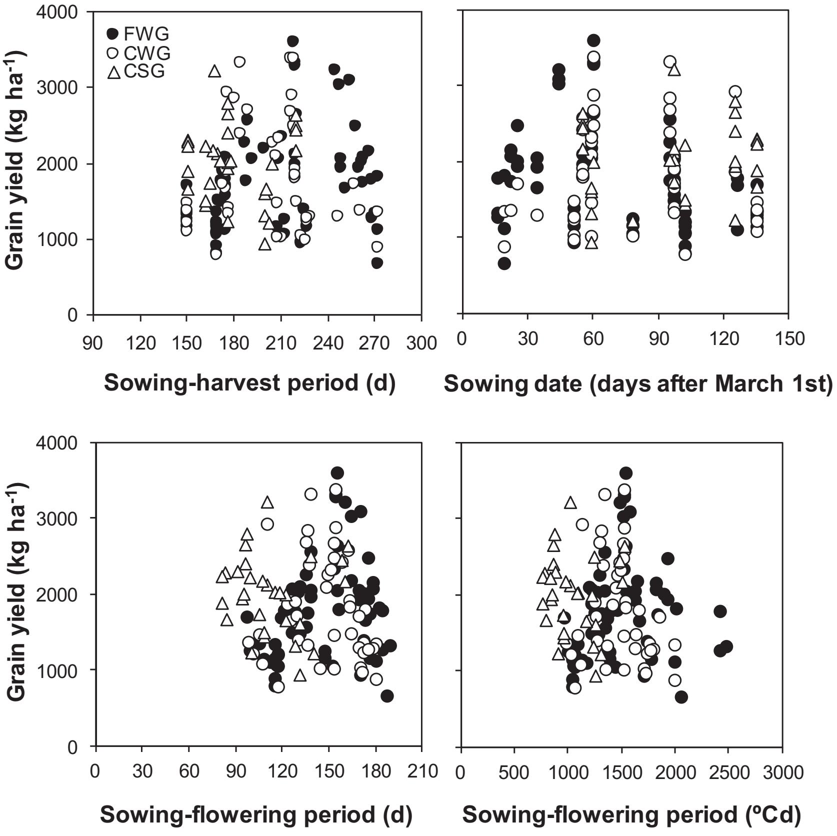

Fig. 2. Relationships between rapeseed grain yield and the duration (days) of the crop cycle (top left panel), sowing date (top right panel), and pre-flowering period expressed as day (bottom left panel) and thermal time (bottom right panel) observed in French winter genotypes (FWG), commercial winter genotypes (CWG), and commercial spring genotypes (CSG) evaluated during three years (2007–2009) in eight locations of the southeastern Pampas.

from 780 to 3380 kg ha^{-1}, and averaged 1700 ± 655 kg ha^{-1}. Spring genotypes (CSG) produced slightly higher yields with less variability, averaging 2010 ± 516 kg ha^{-1} and ranging from 937 to 3217 kg ha^{-1} (Fig. 1).

Total crop cycle duration varied from 150 to 275 d in winter genotypes and from 150 to 220 d in spring genotypes (Fig. 2). In spite of the variability in the cycle duration, grain yield was not related to the duration of any phenological phases in any of the genotype groups analyzed (Fig. 2). Yield was not associated with sowing date ($p > 0.1$). The highest yield (>3000 kg ha^{-1}) were obtained in the range of sowings from April to June, although the lowest yield (<1000 kg ha^{-1}) were recorded into the whole range of sowing dates. The pre-flowering period lasted approximately 70% of the crop cycle duration in winter materials (from 125 to 175 d) and 60% in spring genotypes (from 100 to 125 d). Regarding the length of the crop cycle, spring genotypes registered shorter sowing-flowering period than French and commercial winter genotypes for the whole range of sowing dates (Fig. 3). This trend was consistent when duration of the cycle was measured in days and thermal time. Winter and spring genotypes shortened the cycle as sowing date was delayed at the same rate independently whether the calculation was made in day or degree days (Fig. 3). Thus, pre-flowering period was shortened ca. 0.7 d or 7 °Cd per day of delaying in sowing date from 1st of March (Fig. 3, upper panel). The main differences between spring and winter types were observed in the intercept. Thus, spring genotypes were in average 16 d and 330 °Cd earlier than winter types. When duration of the pre-flowering period was plotted against the average photoperiod of the phase, the general trend was the longer the pre-flowering period the higher the photoperiod. However, a detailed inspection of the data shows that this trend was driven by the winter genotypes as (with the exception of three spring genotypes exposed to photoperiods between 11.5 and 12 h) spring genotypes did not show a consistent trend in their duration of the pre-flowering period as photoperiod was lengthened (Fig. 3, lower panel).

3.2. Principal component analysis of rapeseed cases in the southeastern Pampas region

The PCA of the 129 cases that resulted from the combination of genotype, year, site and sowing date showed two principal axes that explained 60 and 25% of the total variability by yield and phenological stage durations (days) for PC 1 and 2, respectively (Fig. 4). The first ordering axis represented a weighted average of the sowing-flowering (dursf), flowering-harvest (durfh) and sowing-harvest (dursh) periods, while the second axis represented a contrast between yield and the duration of the different stages (Table 3). The biplot of the two first principal components shows the cases with longer crop cycle durations on the left side of axis 1, while the cases with higher yields appear on the upper side of axis 2 (Fig. 4). Both FWG and CWG were present in the four quadrants of the graph, indicating that they covered similar crop cycle durations and yield ranges. In contrast, CSG had a tendency to group in the right upper quadrant, and their projections on the axes indicate that they had medium to short cycle durations and produced medium to high yields (Fig. 4). Sowing dates (March–July) had a high ordering level on axis 1 (early sowing dates on the left side), and the cycle duration was mainly determined by the sowing date, and to a lesser degree by the year (Fig. 4). The duration of the whole cycle (dursh) was more associated with the changes in the pre- (dursf) more than the duration of the post-flowering (durfh) phase. Yield was more associated with durfh than dursf when both spring and winter types were analyzed together (Fig. 4).

When in the PCA both types of cultivars (winter and spring) were analyzed separately, the responses were different (Fig. 5). The winter type genotypes (Fig. 5, upper panel) were ordered as a function of the average value of the cycle durations on axis 1 (68% of the variability) and generated a contrast between yield and cycle duration on axis 2 (23% of the variability). The dursh was similarly explained by the changes in pre- and post-flowering phases and both phases were not associated to yield (see orthogonal vectors in Fig. 5, upper panel). FWG and CWG held similar positions on all the quadrants, indicating a similar behavior for both winter groups. The PCA of spring genotypes (Fig. 5, lower panel) showed different axes arrangement compared to the rest of the groups, and the relationship between post-flowering duration and yield gained particular importance. The first and second axes explained 48 and 27% of the total variability, respectively, being slightly lower than the variability explained in the PCA of the winter genotypes. The cases of short total and pre-flowering durations, located on the left of axis 1, corresponded to July sowing dates; the cases of highest post-flowering

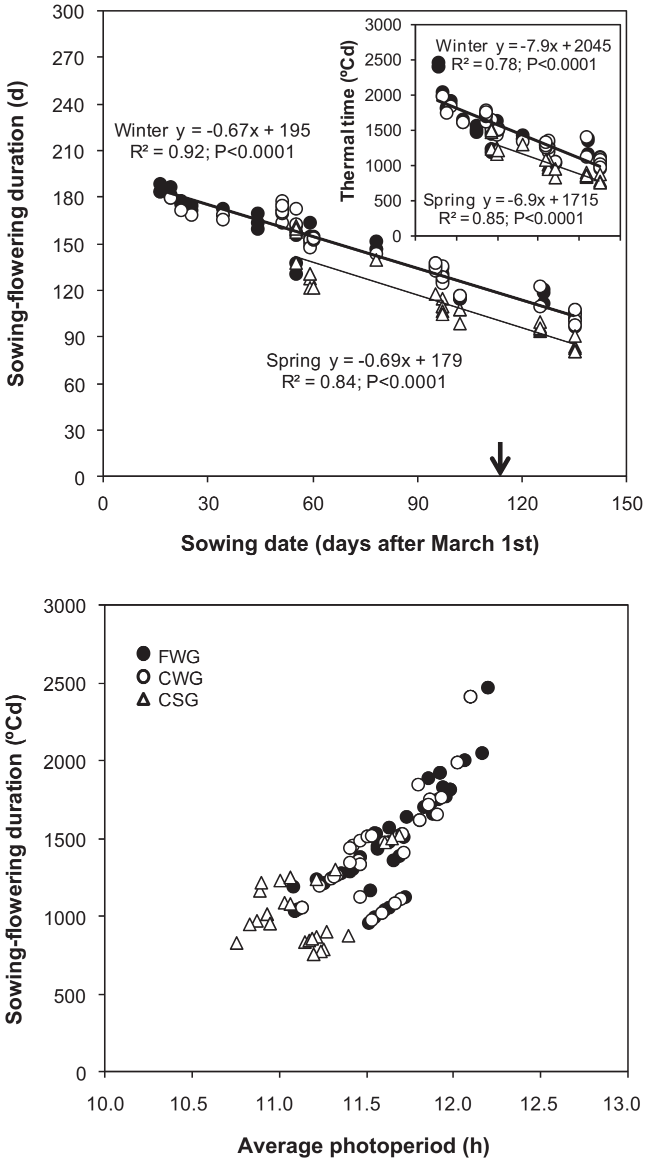

Fig. 3. Relationships between sowing date and the duration of sowing-flowering period expressed as calendar time (upper panel) and thermal time (inset); and relationship between the duration expressed as thermal time and the average photoperiod of sowing-flowering period (lower panel) from French winter genotypes (closed circles), winter commercial genotypes (open circles) and spring commercial genotypes (triangles) of rapeseed evaluated from 2007 to 2009 in the southeastern Pampas. Arrow indicates the time of winter solstice. Linear adjustments of the data are shown.

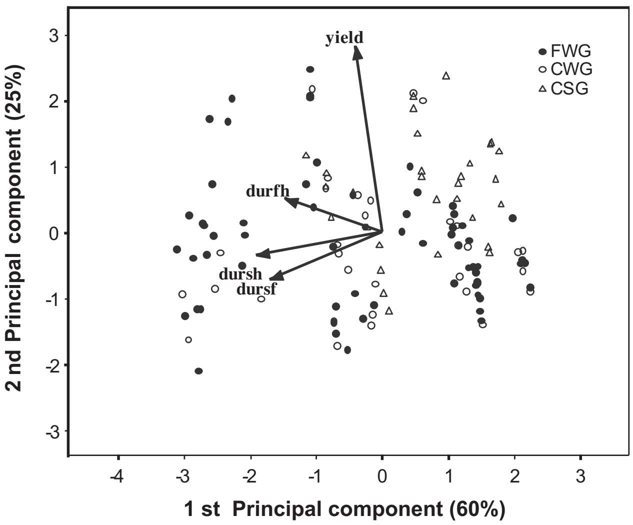

Fig. 4. Principal component biplot and variable vectors included in the analysis of all the observations (129 cases) from French winter genotypes (closed circles), winter commercial genotypes (open circles) and spring commercial genotypes (triangles) of rapeseed evaluated from 2007 to 2009 in eight sites of the southeastern Pampas. Abbreviation of variables: dursf, duration (d) from sowing to flowering; dursh, duration (d) from sowing to harvest; durfh, duration (d) from flowering to harvest.

durations and greatest yields were positioned in the upper part of axis 2 (Fig. 5, lower panel).

3.3. Relationship between yield and environment in the southeastern Pampas

During the three year-experiments there was an important variation in precipitations, temperatures and frost occurrences (Table 4). Precipitations between March and November (i.e. most of the crop cycle) were: 864 mm in Balcarce (2007), 401 mm in Daireaux (2009) and 378 mm in Tres Arroyos (2008). The years 2008 and 2009 were extraordinarily dry due to the occurrence of the climatic phenomenon “La Niña” in the Pampas region. Frost occurrences were very frequent in the whole Pampas region during the three years of the study. Early frosts were recorded in April and May of 2008. Many late frost occurrences were recorded and were particularly frequents during September and October 2009 (Table 4). The year 2007 was very cold (with uncommon snow falls occurred in Balcarce) and late frosts occurred even in November.

Table 3

Eigenvectors of axes 1 and 2 in the PCA for the group of genotypes, and for the winter and spring rapeseed groups evaluated during three years (2007–2009) in eight locations in the southeastern Pampas.

Group	Variable[a]	Eigenvector	
		1	2
All	yield	−0.1122	0.9583
	dursf	−0.5725	−0.2132
	dursh	−0.6404	−0.1023
	durfh	−0.4995	0.1602
Winter (FWG + CWG)	yield	−0.1883	0.9820
	dursf	−0.5612	−0.0986
	dursh	−0.6017	−0.1138
	durfh	−0.5362	−0.1140
Spring (CSG)	yield	−0.0693	0.3664
	dursf	0.7086	−0.1474
	dursh	0.7016	0.2209
	durfh	−0.0282	0.8918

[a] Abbreviation of variables: dursf, duration (d) from sowing to flowering; dursh, duration (d) from sowing to harvest; durfh, duration (d) from flowering to harvest.

Yield was not related to individual environmental variables as mean temperatures, average photoperiod, accumulated incident radiation or accumulated precipitations in the pre- or post-flowering stages when all cases were considered (Table 5). Similarly, the principal component axes were not strongly related to those environmental variables separately (Table 5). Yield, however, was partially explained by the linear combination of environmental factors (Table 6). Thus, for winter genotypes the following model (see Eq. (1)) including pre-flowering radiation (radsf), pre-flowering rainfall (rainsf), post-flowering rainfall (rainfh), and pre-flowering mean temperature (tempsf) explained 50% of the variability in grain yield.

$$\text{Grain yield (winter)} = 3152.7 - 1.12\,\text{radsf} + 8.21\,\text{rainsf} + 7.85\,\text{rainfh} - 226.17\,\text{tempsf}\,(R^2 = 0.50) \tag{1}$$

In the case of the spring genotypes, the only relevant environmental variable associated with yield was the number of days with frost during the critical period of 30 d after flowering (frostcp), although only explained 26% of yield variations (Eq. (2)).

$$\text{Grain yield (spring)} = 2433.4 - 79.85\,\text{frostcp}\,(R^2 = 0.26) \tag{2}$$

The variable frostcp, which ranged from 0 to 14 d, was significantly correlated ($r = 0.70$) to the total days with frost in the whole crop cycle (ranging from 27 to 72 d) and was negatively related to the sowing date and to the flowering date in all the genotype groups (Fig. 6). This means that for every 20 d of delay in the sowing date after March 1st there was one day less of frosting occurrence during the critical period, both in winter and spring genotypes. The linear adjustments also indicate that if there were less than 5 frost occurrences in the rapeseed critical period, flowering must have taken place at the beginning of October (Fig. 6). In line with Eqs. (1) and (2), yield was not related to the frostcp variable during the critical period in winter genotypes, but it was related to the spring genotypes (Fig. 6).

Validation of models predicting rapeseed yields (Eqs. (1) and (2)) were performed using independent data from official CYTs carried out by INTA from 2007 to 2010. Observed and estimated values for winter genotypes were linearly related ($p < 0.0001$) with a coefficient of correlation (r) of 0.56, which is an acceptable value for a broad range of observed rapeseed yield of 780–4100 kg ha^{-1} (Fig. 7). Although the fitted line to the data is located above the 1:1 line, the slope of observed versus predicted relationship (0.85 ± 0.18) was not significantly different from 1 and the intercept (659 ± 384 kg ha^{-1}) not different from 0, indicating that model from Eq. (1) do not significantly overestimate the rapeseed yield of winter genotypes. However, it is important highlight that predicted yields were not uniformly distributed over the 1:1 line and three clear groups were identified. Precipitation during pre- and post-flowering phases was the main environmental attribute that determined the separation among the 3 groups (inset Fig. 7). Low precipitations during both phases determined the lowest yields while the highest yields were associated with high rains during pre- and post-flowering periods. In the case of the intermediate yields, precipitations were enough during pre-flowering but scarce during the post-flowering phase. In spite of the model described in Eq. (1) includes precipitation during both pre- and post-flowering the relative weighting of each phase was not completely satisfactory as probably would be necessary include in the model the interaction between rains during pre- and post-flowering. Conversely, for spring genotypes, the relationship between observed and predicted yield calculated from Eq. (2), considering the number of days with frosts, was weak with a coefficient of correlation of 0.34, i.e., a similar value to that obtained in the model formulation.

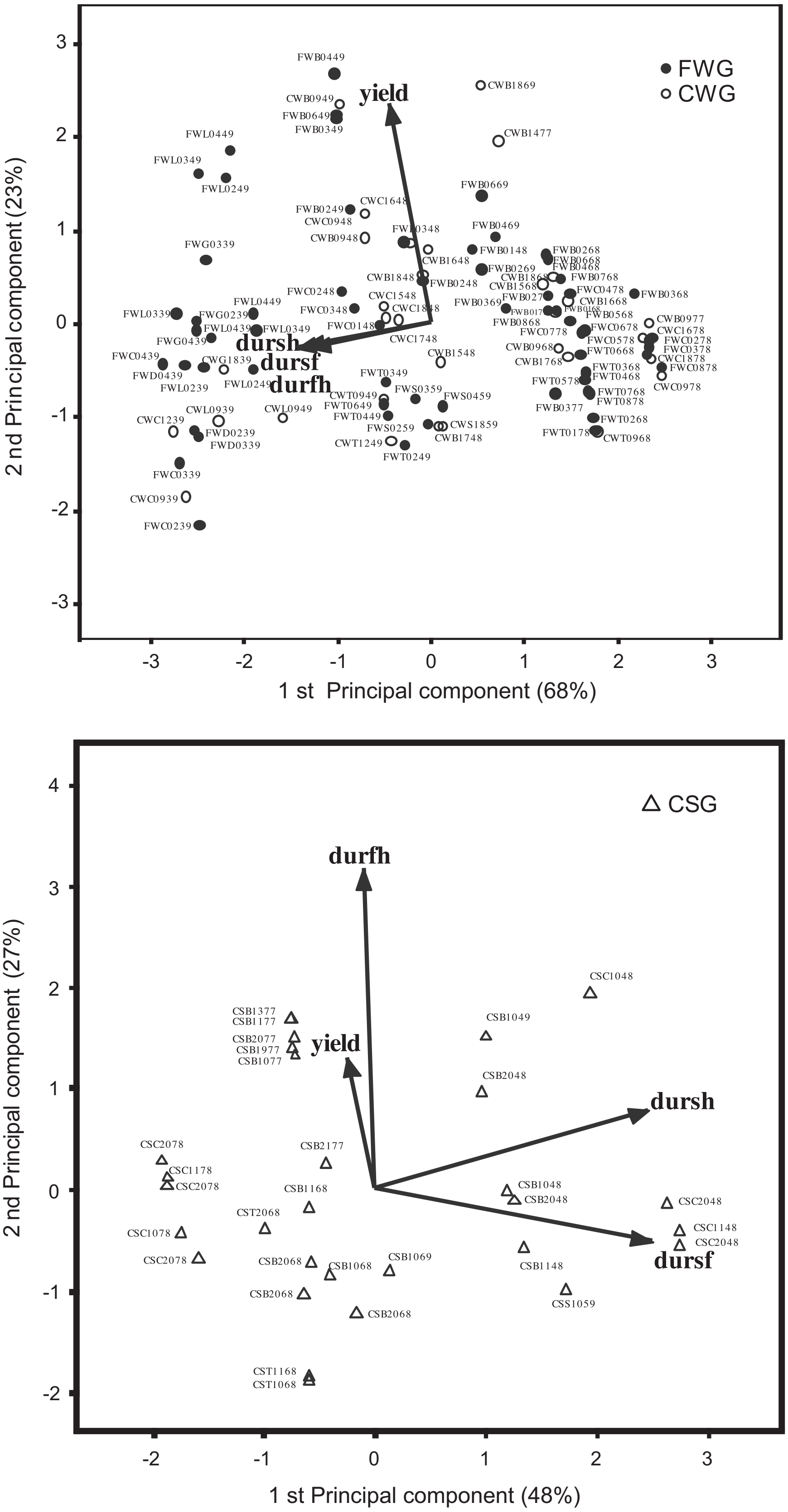

Fig. 5. Principal component biplots and variable vectors included in the analysis of winter (99 cases, upper panel) and spring (30 cases, lower panel) rapeseed genotypes evaluated from 2007 to 2009 in the southeastern Pampas. The observation codes are explained in Section 2.3.

Table 4
Monthly mean temperatures, rainfall and days with frost occurrences (<0 °C) in different sites of the southeastern Pampas from 2007 to 2009.

Month	Year								
	2007	2008			2009				
	Balcarce	Balcarce	Tres Arroyos	Chillar	Balcarce	Daireaux	Tres Arroyos	Chillar	Tandil
Mean temperature (°C)									
March	18.2	18.1	17.9	17.8	20.5	22.0	20.9	19.5	19.6
April	15.3	15.3	14.4	14.4	15.8	17.7	15.6	15.1	14.1
May	9.5	11.6	11.2	10.6	12.7	13.6	12	11.7	11
June	7.6	8.4	7.6	7.4	8.3	8.9	8	7.3	6.8
July	6.0	9.6	8.9	9.5	7.2	7.9	6.6	6.4	5.8
August	6.8	8.8	8.1	8.4	11.8	13.6	11.7	11.7	11
September	12.4	11.1	10.7	10.6	9.2	11.5	9.3	9.3	8.6
October	14.6	13.8	13.8	13.6	13.8	16.4	13.8	13.8	12.8
November	14.7	19.6	20.7	19.8	17.1	19.4	16.7	16.7	16.2
Average	11.7	12.9	12.6	12.5	12.9	14.6	12.7	12.4	11.8
Rainfall (mm)									
March	211	239	178	107	65	43	131	63	35
April	241	16	21	0	44	37	26	30	58
May	26	22	20	10	95	40	41	80	59
June	33	39	27	32	95	0	56	20	30
July	15	75	30	35	71	25	38	37	34
August	22	70	22	47	4	0	4	5	5
September	183	19	38	21	52	99	36	98	62
October	85	28	22	69	30	18	46	34	20
November	48	53	20	83	70	139	69	58	145
Total rain	864	561	378	404	529	401	447	425	448
Frost (days)									
March	0	0	0	0	0	0	0	0	0
April	0	2	5	3	0	0	5	2	1
May	0	11	6	7	1	4	8	6	4
June	1	17	13	11	12	11	11	12	15
July	12	11	10	5	21	16	19	19	19
August	7	18	15	12	2	6	9	8	7
September	0	3	6	8	4	4	13	9	13
October	0	9	7	3	6	0	4	1	5
November	8	2	1	0	2	0	3	0	1
Total frost	28	73	63	49	48	41	72	57	65

The photothermal quotient during the critical period (calculated as the relationship between the incident global radiation and the average mean temperature in the 30 d post-flowering) ranged from 1.0 to 1.75 MJ m^{-2} d^{-1} $°C^{-1}$ and was not related to grain yield in either genotype group (Fig. 8). Similarly, no relationship was found between yield and the variables radiation and temperature analyzed separately.

3.4. *Rapeseed water use efficiency in the southeastern Pampas*

Precipitations during the crop cycle varied among years and sites from 170 to 450 mm, being the years 2008 and 2009 very dry (Table 4). The accumulated precipitations during the crop cycle showed a significant relationship ($p < 0.0001$) with the maximum actual yield values (Fig. 9). Taking account the 90th percentile of the yield distribution the regression adjusted with an intercept of 508.6 kg ha^{-1} and water use efficiency (slope of the regression) of 6.77 kg ha^{-1} for each mm of rainfall. On the other hand,

Table 5
Simple correlation coefficients (*r*) between environmental variables (temperature and average photoperiod, incident radiation and accumulated precipitations) and yield, and principal component axes (PC) for the sowing-flowering (sf) and flowering-harvest (fh) periods using the whole group of rapeseed observations (129 cases) in the southeastern Pampas from 2007 to 2009.

Variable	Period	Yield	PC1	PC2
Temperature	sf	0.18	0.46	0.28
	fh	0.03	0.08	0.02
Photoperiod	sf	0.19	−0.66	0.26
	fh	0.11	0.53	0.08
Radiation	sf	0.20	−0.70	0.39
	fh	0.08	−0.74	0.07
Precipitation	sf	0.35	0.18	0.29
	fh	0.15	−0.76	0.09

Table 6
Multiple linear regression analyses of winter and spring rapeseed yields evaluated in the southeastern Pampas from 2007 to 2009 as a function of the environmental variables: accumulated incident global solar radiation sowing to flowering (radsf), accumulated rainfall for the (rainsf) and flowering-harvest (rainfh) periods, average mean temperature from sowing to flowering (tempsf), frost occurrences in the critical period of 30 d post-flowering (frostcp).

Coefficient	$R^2 = 0.50$		
	Estimate	SE	*p*-Value
Winter genotypes			
intercept	3152.7	660.3	<0.0001
radsf	−1.12	0.31	0.0005
rainsf	8.21	0.99	<0.0001
rainfh	7.85	1.50	<0.0001
tempsf	−226.17	80.76	0.0061
Coefficient	$R^2 = 0.26$		
	Estimate	SE	*p*-Value
Spring genotypes			
intercept	2433.4	158.1	<0.0001
frostcp	−79.85	25.44	0.0040

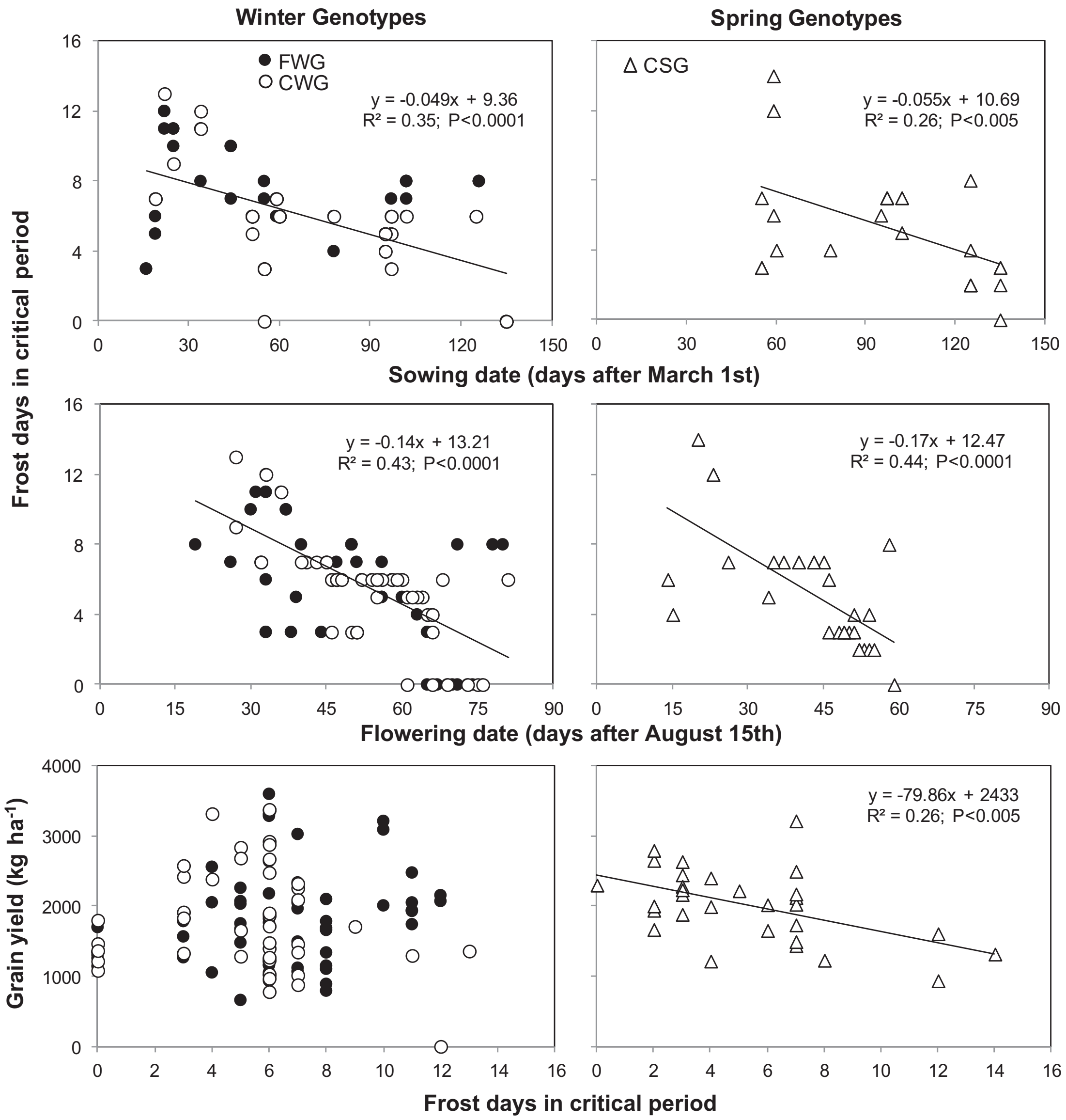

Fig. 6. Relationship between the number of days with frost occurrences in the critical period of 30 d post-flowering and the sowing date (upper panels); flowering date (middle panels); and the relationships between rapeseed grain yield and the number of days with frost occurrences during the critical period (bottom panels) for French and commercial winter genotypes (FWG and CWG; left panels), and commercial spring genotypes (CSG; right panels) evaluated in eight locations in the southeastern Pampas from 2007 to 2009. Linear adjustments of the data are shown.

when regression was fit considering the 50th percentile, the water efficiency was 3.6 kg ha^{-1} for mm and intercept was 583 kg ha^{-1}, whereas the water use efficiency was only of 1.6 kg ha^{-1} for each mm of rainfall for the 10th percentile (Fig. 9). During fallow, precipitations ranged from 0 to 200 mm and from 40 to 300 mm, considering 30 and 60 d before sowing in each experiment, respectively. Considering available water from growing season rainfall plus 60-days fallow rainfall, the regression for 50th percentile adjusted with an intercept of 783 kg ha^{-1} and a median water use efficiency of 1.5 kg ha^{-1} for mm of available water (data not shown).

4. Discussion

4.1. Grain yield variability for winter and spring genotypes

Rapeseed yields in the southeastern Pampas were very variable among sites, sowing dates and years in winter and spring groups of genotypes, ranging from 600 to 3700 kg ha^{-1} (Fig. 1). A high yield variability, ranging from 500 to 4500 kg ha^{-1} with CVs >0.40, was also observed in the national cultivar evaluation network of INTA during the last 4 years and even in the same place and year (Iriarte et al., 2008).

Grain yield range of spring rapeseed genotypes did not differ from winter genotypes (Fig. 1), refusing the general belief, at least for the Argentinean environmental conditions, that winter rapeseed genotypes have a higher yield potential than spring genotypes. The assumption that winter genotypes have higher yield potentials than spring genotypes is based on the longer crop cycle duration in the winter (when are sown early) than in the spring genotypes, that produce more biomass than the spring, assuming a stable harvest index (approximately 0.30), which is translated into higher yields (Diepenbrock, 2000; Berry and Spink, 2006). These premises are probably valid for some European winter season as occur in France and England, but not for other environments where constraints may penalize harvest index throughout a reduction of floret survival and fruit setting. For example, some winter cultivars, with long cycle length are not suitable for Australia environments, because Mediterranean conditions enhance drought and heat stress risk,

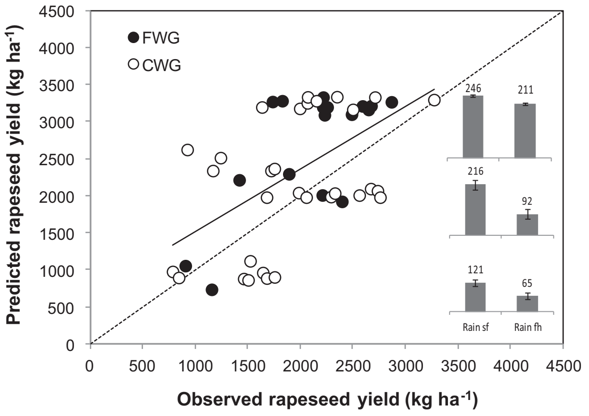

Fig. 7. Relationship between observed and predicted rapeseed yields ($y = 0.85x + 659.5$; $R^2 = 0.31$; $P < 0.0001$; $n = 48$) for French (FWG) and commercial (CWG) winter genotypes, from independent data obtained in official comparative yield trials driven by INTA in Balcarce and Barrow sites (2007–2010). Predicted yield values were calculated from environmental variables using Eq. (1). Three groups of predicted data were observed, and bars indicate the amount of rain (mm, mean ± 1 SE) during pre- and post-flowering for each group. The data source is cited in Section 2.3.

especially on the reproductive stages, due to a delay in the cycle (Robertson and Holland, 2004). Similarly, recent studies in Canada shown that spring genotypes get high yields if they avoid the negative impacts of high temperatures and low precipitation, especially in the early part of the flowering period of the crop (Kutcher et al., 2010). In the southern Pampas, it is probably that winter genotypes with strong vernalization requirements cannot be fulfilled determining excessive crop cycle durations, placing the critical period (early reproductive stages) under unfavorable climatic conditions (see below). Consequently, these environmental constrains counterbalance the potential benefits of longer cycle duration producing greater biomass and yield under environments without the restrictions described above (Fig. 2). These aspects should be confirmed in future trials evaluating biomass production and harvest index in winter and spring genotypes growing in the southeastern Pampas.

4.2. *Sowing date, length cycle and factors controlling yield*

Sowing date (from March to July in this study) was not directly associated to grain yield (Fig. 2), but was a source of variability that affected cycle length and the exposition of the crop to frost during the critical period (Figs. 2 and 6). Thus, frost occurrence was negatively related to yield only in spring genotypes (Fig. 6). Linear regressions indicated that placing flowering time at the beginning of October caused a decrease in the occurrence of frost events to less than 5 d in average during the critical period (Fig. 6). Therefore, the southeastern Pampas environments should be considered areas of high frost risk during a considerable part of the rapeseed crop cycle (Table 4), especially for spring genotypes, in which yields were affected by frost occurrences during the critical period (Eq. (2)). The best-adapted genotypes should show mechanisms of frost tolerance, like the accumulation of osmotic substances in plant tissues and high wax contents in the cuticle (Rife and Zeinalib, 2003). An extended flowering period could be another mechanism for some clusters of flowers to escape from frost damage (Tayo and Morgan, 1979), although later flowering times for avoiding frost damage could determine negative effects on grain size and oil content in grains due to the exposure to higher temperatures during grain filling, penalizing not only yield but also grain quality (Angadi et al., 2000; Aksouh et al., 2001). The negative effects of this strategy were evident in winter genotypes, in which delayed sowing dates determined the lack of fulfillment of vernalization requirements delaying excessively flowering time and penalizing yield due to un-favorable conditions during grain filling.

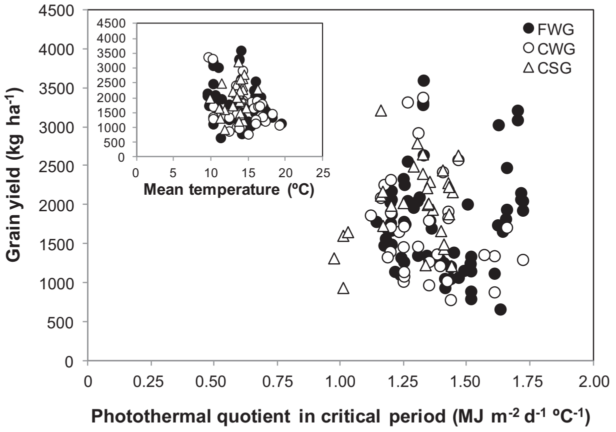

Fig. 8. Relationship between rapeseed grain yield and the photothermal quotient in the critical period during 30 d post-flowering for French winter genotypes (FWG), commercial winter genotypes (CWG), and commercial spring genotypes (CSG) evaluated in eight locations in the southeastern Pampas from 2007 to 2009. The inserted figure shows no relationship between yield and mean temperature during the critical period.

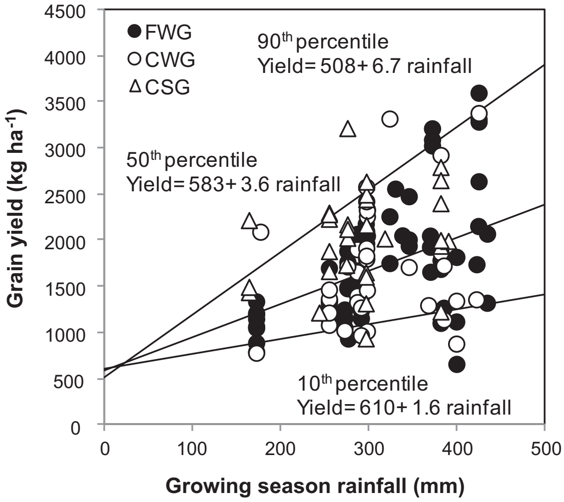

Fig. 9. Relationship between rapeseed grain yield and the accumulated precipitations during the crop cycle for French winter genotypes (FWG), commercial winter genotypes (CWG), and commercial spring genotypes (CSG) evaluated for three years (2007–2009) in eight locations in the southeastern Pampas. Linear adjustments for the 10, 50 and 90th percentile are shown.

As expected, delays in the sowing date in winter and spring genotypes shortened the duration of the pre-flowering period, when expressed both in calendar and thermal time (Fig. 3). However, the duration of the phase from sowing to flowering, when measured in thermal units, tended to increase, even when the photoperiod was extended (conversely to was expected in a long day species as rapeseed), evidencing a lack of fulfillment of vernalization requirements especially in the winter genotypes, although it was evident in some spring genotypes too (Miralles et al., 2001; Gomez and Miralles, 2011). Different studies in wheat (Miralles et al., 2007) and in rapeseed showed a higher photoperiodic sensitivity in winter than in spring cultivars (King and Kondra, 1986; Miralles et al., 2010). In the analysis carried out in the present study, it was not possible a clear identification of different photoperiod sensitivities between winter and spring genotypes due to the masked effects given by vernalization in the former genotypes. In fact, the rate of shortening of the cycle from sowing to flowering measured per day or thermal time per unit of delay in sowing date was similar in winter and spring types (see Fig. 3). Manipulative studies are needed to determine differences in photoperiod sensitivity and vernalization in winter and spring genotypes introduced in high southern latitudes.

The duration of the phenological phases, which was affected by the year and the sowing date, was related in a different way to the PCA yield axis according to the genotype group. However, no direct relationship was observed between yield and cycle duration (Fig. 2). These results contrast, at least for the Argentinean environmental conditions, with the suggestion that longer cycle duration determine greater biomass and a higher yield (Diepenbrock, 2000; Berry and Spink, 2006). In fact, Quijada et al. (2004) introgressed French winter germplasm into hybrid spring canola and found that earlier flowering lines tended to produce higher yields in the USA and Canada. Spink et al. (2009) also pointed out that the yield generation period should be extended to increase winter rapeseed yields in the UK, and in line with Spink's data, Agosti (2011) observed a positive relationship between yield and the post-flowering duration in irrigated commercial winter and spring genotypes with no frost damage. The relationship between yield and post-flowering duration should be more deeply analyzed, as this attribute could be useful as a selection criterion in genotypes grown under environments with a low risk of drought and frost occurrences.

Differences in winter and spring genotype yield formation were also evident in the factors that were included in the multiple regression yield models (Table 6); the relevant variables were completely different for each genotype group (Eqs. (1) and (2)). Even though these models only explain part of the observed yield variability (50% at most), they are the first quantitative approximation to rank the environmental factors affecting yield in the southeastern Pampas region. The validation of the prediction yield model for winter genotypes (Fig. 7) confirms the relevance of environmental variables such as accumulated radiation up to flowering, rain in the whole crop cycle, and mean temperature up to flowering, which may be a first step to (i) model more complex routines to predict winter rapeseed yields in the southern Pampas, and (ii) focus on environmental drivers for specific crop phases which deserve further study. Clearly, although validation was acceptable, it is necessary improve the model as data were not layout throughout the 1:1 line. Thus, model should be improved in characterize the rain distribution during for pre- and post-flowering periods and include an interaction factor between rains in both periods. For example, excessive precipitation during the pre-flowering phase could determine an excessive production of biomass at flowering that could not be sustained during post-flowering period whether rains become scarce and thereby the yield will be low as canopy transpiration cannot be fulfilled. On the other hand, the limited ability to predict grain yield of spring genotypes may indicate (i) that other environmental variables are more relevant (such as maximum or minimum temperatures, rainfall thresholds, and intercepted instead of incident radiation), and/or (ii) the existence of other sub-periods of development of higher sensitivity, different from the pre- and post-flowering periods considered in this work. Clearly, more research is needed to understand the causes of yield variability for spring rapeseed growing in the southeastern Pampas.

4.3. Relationship between grain yield and photothermal quotient

In this study, no relationship was found between yield and the photothermal quotient (i.e., incident radiation/mean temperature ratio) in the 30 d post-flowering critical period (Fig. 8). These results are in agreement with those of Agosti (2011) who evaluated 24 commercial genotypes under field conditions (in Buenos Aires) and considered the critical period to range from 0 to 350 °C d post-flowering. All these findings could indicate that (i) the photothermal ratio is not a good indicator of the grain number for rapeseed, as happens with soybeans and other branched crops (see a revision in Sadras and Calderini, 2009), and/or (ii) the period of 30 d post-flowering does not correctly encompass the critical period when the number of grains are defined in rapeseed, although this period is within the range described in the literature with values of one week (Mingeau, 1974), two weeks (Mendham et al., 1981) and/or to 350 °Cd which represent 30–40 d post-flowering (Habekotté, 1997). Preliminary results indicate that intense shading (−60 and −80% of the incident radiation) during 20 d can reduce grain yield of spring genotypes in a similar magnitude when applied early (7–27 d after flowering) or late (27–47 d after flowering) in the reproductive period, indicating that the duration of the critical period should be extended to 45–50 d after the beginning of flowering (equivalent to 850 °Cd, base temperature = 0 °C) in spring modern genotypes (Rondanini et al., unpublished). Trials like these will provide direct experimental evidence on the definition of the critical period associated with grain yield in modern spring and winter rapeseed genotypes.

Another important point that should be considered is that, in the present study, the photothermal quotient was calculated using the incident instead of the intercepted radiation of the crop during the critical period, which represents the real radiation that is captured by the crop to generate assimilates thereby giving a physiological meaning to the quotient. Experiments under controlled conditions, where intercepted radiation and post-flowering temperature can be manipulated, would help to determine if the lack of relationship between yield and the photothermal quotient is real and consistent or whether it only reflects unknown yield compensation mechanisms in rapeseed (Wang et al., 2011). These experiments are currently taking place with spring genotypes in Argentina.

4.4. Rain variability and WUE

Among the sources of interannual variability that affected genotype performance, precipitation was the most important, varying greatly throughout years (150–450 mm in the whole crop cycle). Years 2008 and 2009 were particularly dry (Table 3) due to the "La Niña" climatic phase, causing the most intense and long drought in the region since the last 70 years. The maximum WUE value observed in the present study (Fig. 9) was similar to that of 7.4 kg ha^{-1} mm^{-1} observed in Australia (Cocks et al., 2001) for a similar seasonal water supply, and falls within the wide range cited in the rapeseed literature (4–14 kg ha^{-1} mm^{-1}; Taylor et al., 1991; Hocking et al., 1997; Grey, 1998; Cocks et al., 2001; Robertson and Holland, 2004). In Australia, WUE variability was related to rainfall distribution in different locations (Robertson and Kirkegaard, 2005); in the southern Pampas, the impact of rainfall distribution has to be further investigated. Contrary to expectations, the maximum WUE intercept was positive in our study, sub-estimating the soil evaporation and indicating that maximum yield values of 500 kg ha^{-1} that could be attained without rainfall during the crop cycle. This value contrasts with the 120 mm needed to obtain a minimum rapeseed yield in Australia (Robertson and Kirkegaard, 2005). This difference could be due to (i) the substantial amount of rainfall during fallow in the southeastern Pampas, which in this study ranged from 40 to 300 mm during the 60 d previous to sowing, and (ii) the high water holding capacity in the southeastern Pampas soils that can reach 1.5 mm cm^{-1} (Travasso and Suero, 1994).

On the other hand, shallow soil depths and compacted horizons in some sites like Tandil, Balcarce and Chillar can reduce the holding capacity (Sadras and Calviño, 2001). Restrictions to taproot growth, even when water was available in the soil, were pointed out as an important yield-limiting factor in southern Australia (Lisson et al., 2007) and Europe (Valantin-Morison and

Meynard, 2008). This factor could be involved in the wide range of yields observed in the southern Pampas for rainfalls higher than 300 mm since no-tillage systems could have caused sub-surface soil compaction (Tolon-Becerra et al., 2011). The deep rapeseed rooting system could represent an advantage to the water economy (Liu et al., 2011) especially in the west of the southern Pampas, where soils are deeper and sandier (Hall et al., 1992) without soil impedances for the root system. Regional studies that include measurements like available water present at sowing, in-crop evapotranspiration and available soil water remaining at harvest will be necessary to improve the quantification of the impact of available soil water on the rapeseed yield variability in the southern Pampas.

5. Conclusions

Winter rapeseed hybrids of French origin evaluated from 2007 to 2009 produced similar yield averages and variability (600–3700 kg ha^{-1}, CV 40%) as the commercial genotypes available in central-south Buenos Aires province, Argentina. Contrary to the general belief, spring genotype yields were not diminished, respect to the winter types, indicating that, under cool environments, winter genotypes do not necessarily yield more than spring genotypes. Rapeseed grain yield was not related to the photothermal ratio 30 d post-flowering. Multiple regression models showed that rainfall during the crop cycle and frost occurrences during flowering were the most important yield-limiting factors for winter and spring genotypes, respectively. While the model developed for winter genotypes adequately estimated rapeseed yield from independent data, the simple model used to characterize yield in spring genotypes did not fit when independent data were used. The WUE ranged from 1.6 to 6.7 kg ha^{-1} mm^{-1}, comparable to values obtained for the same crop under different environments around the world.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eja.2013.01.008.

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