Field Crops Research 127 (2012) 203–214

Contents lists available at SciVerse ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Oil quality of maize and soybean genotypes with increased oleic acid percentage as affected by intercepted solar radiation and temperature

S.G. Zuil[a], N.G. Izquierdo[b,c], J. Luján[d], M. Cantarero[d], L.A.N. Aguirrezábal[b,c,*]

[a] Instituto Nacional de Tecnología Agropecuaria INTA Reconquista, Argentina
[b] Laboratorio de Fisiología Vegetal, Facultad de Ciencias Agrarias (Universidad Nacional de Mar del Plata), Balcarce, Argentina
[c] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
[d] Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba C.C. 509, 5000 Córdoba, Argentina

ARTICLE INFO

Article history:
Received 18 February 2011
Received in revised form
12 November 2011
Accepted 15 November 2011

Keywords:
Oil
Oleic acid
Intercepted PAR
Temperature sensitivity
Zea mays L.
Glycine max (L.) Merr.

ABSTRACT

Oil fatty acid composition of traditional genotypes of several crops including maize and soybean is affected by intercepted solar radiation per plant and temperature during grain filling. The effect of intercepted radiation on oil fatty acid composition of genotypes with increased oleic acid percentage of maize and soybean is unknown. Likewise, on such kind of maize genotypes, no studies have been performed about the effect of temperature on the oleic acid percentage. The objective of this work was to investigate and model the effect of intercepted solar radiation per plant and daily mean temperature during grain filling on the oleic acid percentage in the oil of maize and soybean genotypes with increased oleic acid grown under non limiting conditions. Field experiments were conducted in Balcarce and Córdoba in two growing seasons. An experiment with maize genotypes was also conducted in two sowing dates in Pergamino. The effect of intercepted solar radiation during grain filling on oil fatty acid composition was studied by shading and thinning plants. To evaluate the effect of daily mean temperature, plants were exposed to different temperatures during grain filling in two experiments performed in greenhouse and growth chambers. At harvest oil fatty acid composition was determined by gas–liquid chromatography. Intercepted solar radiation per plant or temperature increased the oleic acid percentage between 9 and 30 percentage points depending on the species and genotype. In both species, genotypes with increased oleic acid percentage presented a higher sensitivity of oleic acid percentage to variations in intercepted solar radiation than traditional ones. The effect of temperature on oil fatty acid composition was also higher in maize genotypes with increased oleic acid percentage than in the traditional one of the same species. In soybean, the sensitivity of oleic acid percentage to temperature was higher in one genotype and lower in the other as compared to the traditional one. Oleic acid percentage was linearly related to DMT but curvilinearly related to ISR per plant, reaching a maximum concentration of this fatty acid at high levels of irradiance. For both species, models that consider the additive effects of intercepted solar radiation and temperature were established. Predictions of the models were validated with data from six field independent experiments. The models adequately estimated ($r^2 \geq 0.65$) the oleic acid percentage of these genotypes grown under different temperatures and ISR per plant during grain filling from these experiments. These results could help to identify crop management practices (e.g. sowing dates, locations, sowing density), in the view to obtain a given oil quality when growing maize and soybean with increased oleic acid percentage.

1. Introduction

Vegetable oil quality is linked to fatty acid composition. Oleic acid is nowadays considered as the preferred fatty acid for edible purposes, because it combines a hypocholesterolemic effect and a high oxidative stability (Mensink and Katan, 1989). Oils with an increased oleic acid percentage have many cooking and health benefits when compared to oils with increased saturated or polyunsaturated fatty acids (Erkkila et al., 2008). Also, the biofuel synthesized from oils with increased oleic acid percentage presents improved quality parameters of biodiesel (Durrett et al., 2008).

Abbreviations: ISR, intercepted solar radiation; DMT, daily mean temperature.

* Corresponding author at: Unidad Integrada Facultad de Ciencias Agrarias (UNMdP), Estación Experimental Agropecuaria INTA Balcarce, Ruta 226 km 73.5 C.C. 276, 7620 Balcarce, Argentina. Tel.: +54 02266 439100; fax: +54 02266 439101.
E-mail addresses: szuil@correo.inta.gov.ar (S.G. Zuil), nizquierdo@balcarce.inta.gov.ar (N.G. Izquierdo), salserocba@yahoo.es (J. Luján), mcantare@agro.unc.edu.ar (M. Cantarero), laguirre@mdp.edu.ar (L.A.N. Aguirrezábal).

0378-4290/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2011.11.019

It is well known that the oleic acid percentage is affected by environmental conditions during grain filling in traditional genotypes of several species including maize and soybean, two of the most cultivated species around the world (e.g. Kane et al., 1997; Strecker et al., 1997). Daily mean temperature (DMT) during grain filling accounted for most of the variation in oleic acid percentage of traditional maize and soybean crops grown in several locations and sowing dates. Intercepted solar radiation (ISR) per plant during grain filling also affected the oleic acid percentage in maize and soybean. Increasing DMT or ISR per plant increased the oleic acid percentage in traditional genotypes of both species (Izquierdo et al., 2009). These environmental factors additively contribute to oleic acid percentage in the oil of a traditional sunflower genotype (Echarte et al., 2010).

Genotypes with increased oleic acid percentage have been developed in sunflower, rape, soybean, maize and other species. Mutations in these genotypes produce a low total activity of the desaturases enzymes. A high stability of oil fatty acid composition independent from the growing environment is a key trait in breeding programs of genotypes with increased oleic acid percentage. Important progress has been achieved in sunflower and rape, where genotypes with increased oleic acid percentage have been reported to be less affected by environmental conditions than traditional ones (e.g. Schierholt and Becker, 2001; Triboi-Blondel et al., 2000). Studies about the effect of intercepted radiation on fatty acid composition of genotypes with increased oleic acid concentration of soybean and maize have not been performed. Also, investigations comparing the effect of temperature during grain filling among traditional and increased fatty acid composition of maize has not been previously developed.

The response of oil fatty acid composition to temperature and intercepted solar radiation in genotypes with increased oleic acid could not be “a priori” predicted from the behavior characterized on traditional genotypes nor from genotypes with increased oleic acid composition of other species, as the mutated genes could not be the same in different species and/or genotypes within the same species (e.g. Takagi and Rahman, 1996; Fernández-Martínez et al., 2004; Alt et al., 2005). The performance of fatty acid composition of sunflower and rape genotypes with increased oleic acid percentage compared to traditional ones (a higher stability of its fatty acid composition) could be different in other species. For instance, the literature is controversial on this trait in soybean. Primomo et al. (2002) reported a lower sensitivity of oil fatty acid composition to environment of soybean genotypes with increased oleic acid percentage compared to traditional ones. On the opposite, Oliva et al. (2006) found that two soybean genotypes with increased oleic acid percentage were more affected by temperature than traditional ones when they were grown under different sowing dates and locations. Differences between these results could partially be accounted for by the effect of temperature among sowing dates or locations (not analyzed in the work of Primomo et al., 2002) but also by other factors as ISR that was not taken in account in none of these works. A more comprehensive knowledge of the relative stability of oil fatty acid composition of increased oleic acid percentage genotypes of maize and soybean could be obtained by comparing responses of these genotypes with that of traditional genotypes to ISR per plant and DMT during grain filling. Based on the literature previously mentioned we hypothesize that changes in ISR and DMT have a lower effect on fatty acid composition in genotypes with increased oleic acid percentage of soybean and maize compared to the traditional ones.

Knowing the effect of ISR per plant and DMT during grain filling on oleic acid percentage in the oil of genotypes with increased oleic acid percentage could be useful for (i) adjusting agronomic management tools to obtain a determinate oil quality, (ii) improving the current knowledge of the mechanisms involved in the modulation of the fatty acid composition by the environment and (iii) to better modeling the effects of environmental conditions during grain filling on the oil fatty acid composition of crops cultivated under different growing conditions. The objective of this work was to investigate and modeling the effect of ISR per plant and DMT during grain filling on oleic acid percentage in the oil of maize and soybean genotypes with increased oleic acid percentage grown under non limiting water and nutrient conditions. To investigate and model the variations in fatty acid composition under a wide range of variation of ISR and DMT during grain filling (i) field experiments were conducted including treatments applied to modify intercepted radiation per plant in two growing seasons. (ii) Plants were grown in growth chambers at different temperatures and (iii) plants were grown in the field at different locations situated at different latitudes and in the greenhouse in order to enlarge the explored range of ISR and DMT. Predictions of the established models were validated with results from field independent experiments. Other fatty acids concentrations were also analyzed to have a complete overview of the integrate response of oil quality to these environmental factors.

2. Materials and methods

In maize, two experimental hybrids (HO1 and HO2, Eyherabide, G., Percibaldi M. Borrás, F., INTA Pergamino breeding program) with increased oleic acid percentage (between 50 and 60% oleic acid, G. Eyherabide, Personal Communication) and a traditional hybrid (DK 615, Monsanto Argentina S.A.) with an oleic acid percentage between 20 and 27% (Izquierdo et al., 2009) were studied. In soybean, studies were performed in M23 (Monsanto Argentina S.A.) and N98-4445A (Nidera S.A.) cultivars with increased oleic acid percentage (between 40 and 50% oleic acid percentage, Oliva et al., 2006) and a traditional cultivar (DK 5520, Monsanto Argentina S.A.) with an oleic acid percentage between 20 and 25% (A. Peper, Personal Communication).

2.1. Field experiments

Field experiments were conducted in three locations (named hereafter as *radiation experiments*) to evaluate the effect of intercepted solar radiation on oil fatty acid composition. Two field experiments were conducted at the Instituto Nacional de Tecnología Agropecuaria (INTA) Balcarce Experimental Station, Argentina (37°45′S, 58°18′W) during the 2006–2007 (RB1) and 2007–2008 (RB2) growing seasons and two at the Universidad Nacional de Córdoba, Argentina (31°19′S, 64°13′W) during the 2006–2007 (RC1) and 2007–2008 (RC2) growing seasons. Balcarce and Cordoba present different average temperatures during the maize and soybean growing seasons (18 °C versus 21 °C approximately). Two experiments were performed at the Instituto Nacional de Tecnología Agropecuaria (INTA) Pergamino Experimental Station, Argentina (33°S, 60°O) during the 2006–2007 growing season in two sowing dates (RP1 and RP2, Table 1) in order to enlarge the explored range of ISR and DMT. Soils at the experimental sites were Typical Argiudol at Balcarce and Pergamino and Entic Haplustol at Córdoba (USDA Soil Taxonomy). Mean plant densities were 7 and 20 pl m^{-2} in maize and soybean, respectively (Table 1). Soybean seeds were inoculated. Soil fertility was enough in all the experiments to attain the maximum yield of the crops grown under non limiting water conditions (Andrade et al., 2000). Rainfall was complemented with irrigations to avoid water deficit. Pest and diseases were adequately controlled.

The experiments conducted in Balcarce and Cordoba were designed as split plots with three replicates. In RB1 and RC1, the species were assigned to the main plots, genotypes were assigned

Table 1
Mean plant density (pl m^{-2}) of the control, dates of sowing and applied treatments in maize and soybean genotypes for radiation experiments (RB 1-2, RC1-2 and RP1-2) and temperature experiments (Tgc and Tgh). Treatments consisted in different levels of ISR per plant or different day/night temperatures during grain filling. S 80%: shaded 80% and S 50%: shaded 50%.

Exp.	Latitude °S	Species	Genotypes	Density	Sowing date	Treatments
RB1	37	Maize	HO1, HO2 DK 615	7.2	11/2/2006	S 80%, thinning, control
		Soybean	M23 DK 5520	19.0	11/2/2006	S 80%, thinning, control
RC1	31	Maize	HO1, HO2 DK 615	6.5	11/21/2006	S 80%, thinning, control
		Soybean	M23 DK 5520	20.0	11/21/2006	S 80%, thinning, control
RP1	33	Maize	HO1, HO2	7.2	09/18/2006	Control
RP2	33	Maize	HO1, HO2	7.1	10/29/2006	Control
RB2	37	Maize	HO1, HO2 DK 615	7.5	11/1/2007	S 80%, S 50%, thinning, control
RC2	31	Soybean	M23 N98-4445A DK 5520	22.0	11/15/2007	S 80%, S 50%, thinning, control
Tgc		Maize	HO1, HO2 DK 615	–	02/02/2008	16/14 °C, 22/20 °C, 28/26 °C
		Soybean	M23 N98-4445A DK 5520	–	02/02/2008	16/14 °C, 22/20 °C, 28/26 °C
Tgh		Maize	HO1, HO2	–	10/23/2007	Control
		Soybean	M23 DK 5520	–	02/02/2008	Control

to the subplots and treatments were assigned to the sub-subplots. In RB2 and RC2, genotypes were assigned to the main plots and treatments were assigned to the subplots. In RP1 and RP2, the maize genotypes were sown in plots with two replicates. In all cases, experimental units were four rows 0.7 m apart and 5 m long. Phenology was registered according to Ritchie et al. (1997) in maize and (Fehr and Cavinness, 1977) in soybean. In maize, plants of the two central rows were tagged approximately 15 days before silking and apical ears were bagged before silk emergence and self-pollinated. Silking date of the apical ear (at last one visible silk) of each tagged plant was registered. In both species, flowering of a plot was registered when 95% of the plants had flowered.

At the beginning of the grain filling (20–25 days after R1 in maize and R5 in soybean), the following treatments were applied to produce variations in the level of ISR per plant: (i) 80% shaded (S 80%); (ii) 50% shaded (S 50%); (iii) untreated plots (control); and (iv) uniform plant thinning until a final density corresponding to the half of the initial density (thinning). In shaded treatments, black, synthetic and neutral mesh cloth was used in order to reduce the incident radiation by 50 or 80%.

Global daily incident radiation was measured with a pyranometer (LI-200SB; LI-COR, Lincoln, NE) located 800 m approximately from the experiments. Daily incident radiation corresponding to the photosynthetically active range of the spectrum was calculated as 0.48 × global daily incident radiation. In the field experiments, the proportion of solar radiation intercepted by the crop at noon was determined according to Gallo and Daughtry (1986) as (1 − Rb/Ro), where Rb is the radiation measured below the last green leaf, and Ro is the radiation measured above the canopy. Rb and Ro were weekly measured at solar noon (±1 h), with a line quantum sensor (LI-191SB; LI-COR, Lincoln, NE). The daily proportion of ISR between two measurements was calculated by linear interpolation. Daily ISR per plant was calculated as the product of daily incident solar radiation and daily proportion of ISR divided by the plant density. For both species, a wide range of ISR per plant during grain filling was obtained (Table 2).

Air temperature was measured in the plots with thermistors (Cavadevices, Buenos Aires, Argentina) previously calibrated with meteorological station data. Air temperature was registered every 60 s and hourly averages were recorded with dataloggers (Cavadevices, Buenos Aires, Argentina). All temperature sensors were previously cross-checked and the maximum difference between sensor measurements was 0.1 °C. Radiation treatments slightly modified the temperature in the plots (maximum difference between treatments = 0.9 °C).

2.2. Growth chamber and greenhouse experiments

Experiments were performed in growth chambers (Tgc) and in a greenhouse (Tgh) to enlarge the range of DMT during grain filling (named hereafter *temperature experiments*). Plants were sown in 10-L pots filled with soil. Maize and soybean cultivars were sown in Tgc experiment on 02/02/2008 and in Tgh experiment on 10/23/2007 (maize) and 2/02/2008 (soybean). After emergency, plants were thinned to one (maize) or three (soybean) per pot. Plants were fertilized according to Izquierdo et al. (2009). Pots were irrigated every 12 h to avoid water stress. Air temperatures in the growth chambers were registered every 60 s and hourly averages were recorded with dataloggers (Cavadevices, Buenos Aires, Argentina). Plants were exposed to three day/night temperature regimes during grain filling: 16/14 °C, 22/20 °C and 28/26 °C. Temperature regimes were achieved using growth chambers (Refrimax S.R.L., Mar del Plata, Argentina) with 12-h photoperiod and incident photosynthetically active radiation at the top of the plants of $690 \pm 75\ \mu mol\ m^{-2}\ s^{-1}$. Shorter plants were raised to receive the same incident radiation at the top. In Tgh, DMT

Table 2
Cumulative ISR per plant (MJ $plant^{-1}$) and DMT (°C) during grain filling in maize and soybean from *radiation experiments*. The grain filling period was considered as flowering-physiological maturity in maize and R5-physiological maturity in soybean.

Species	Exp.	DMT	Cumulative ISR per plant			
			Shaded 80%	Shaded 50%	Control	Thinning
Maize	RB1	18.3 ± 3.6[a]	9.1 ± 0.9	–	40.9 ± 4.2	62.6 ± 9.9
	RB2	20.2 ± 2.9	8.1 ± 1.1	20.8 ± 1.8	40.3 ± 4.3	65.2 ± 10.3
	RC1	20.9 ± 3.1	10.1 ± 0.5	–	43.4 ± 4.9	69.3 ± 10.4
	RP1	22.0 ± 2.4	–	–	42.8 ± 2.8	–
	RP2	21.3 ± 2.1	–	–	44.5 ± 3.7	–
Soybean	RB1	15.3 ± 3.9	2.4 ± 0.6	–	11.8 ± 0.0	23.2 ± 0.2
	RC1	20.3 ± 3.1	3.9 ± 0.1	–	19.3 ± 0.7	38.2 ± 1.1
	RC2	20.4 ± 3.3	4.1 ± 1.0	11.8 ± 2.6	20.1 ± 3.6	33.2 ± 6.6

[a] Standard deviation.

Table 3
Mean plant density (pl m^{-2}) of the control, dates of sowing, applied treatments, daily mean temperature (DMT, °C) and intercepted solar radiation (ISR) per plant during grain filling (MJ pl^{-1}) in maize and soybean genotypes from the validation experiments (VB1, VB2, VB3, VC1, VR1 and VR2). Treatments consisted in different levels of ISR per plant. S 80%: shaded 80% and S 50%: shaded 50%.

Exp	Latitude °S	Species	Genotypes	Density	Sowing date	Treatments	DMT	Cumulative ISR per plant
VB1	37	Maize	HO1, HO2	6.0	11/11/2008	S 80%,	17.1	19.5 ± 0.1
						S 50%	17.6	35.3 ± 0.3
						Control	18.8	55.3 ± 3.0
						Thinning	19.0	77.4 ± 3.2
		Soybean	DK 5520	19.0	11/24/2010	Control	18.7	21.1 ± 0.1
VB2[a]	37	Maize	DK 615	7.0	11/12/2001	S 80%,	18.0	32.4 ± 4.3
						S 50%	18.5	41.1 ± 8.6
						Control	18.5	59.8 ± 5.0
						Thinning	18.5	68.6 ± 7.1
VB3[a]	37	Maize	DK 615	7.0	10/25/2004	S 80%,	18.8	34.9 ± 2.4
						S 50%	19.0	43.7 ± 2.7
						S 50% + Thinning	18.9	51.2 ± 3.6
						Control	20.0	65.1 ± 7.7
						Thinning	19.4	83.7 ± 7.9
VC1	31	Soybean	DK 5520	19.0	12/09/2010	Control	18.8	14.2 ± 1.3
VR1	29	Soybean	DK 5520	18.0	09/27/2010	S 80%	25.2	4.5 ± 1.0
						Control	24.5	33.4 ± 6.3
VR2	29	Soybean	DK 5520	18.0	11/10/2010	Control	23.6	33.1 ± 2.6

[a] More details about these experiments see Izquierdo et al. (2009).

during grain filling were 18 °C and 12 °C for maize and soybean, respectively.

In all the experiments, physiological maturity was estimated visually from the black layers of the grain in maize (R6, Ritchie et al., 1997) and the brown color of the pods in soybean (R8, Fehr and Cavinness, 1977). Plants were harvested at physiological maturity.

2.3. Validation experiments

Independent data to validate the models were obtained from field experiments conducted with the maize hybrids HO1 and HO2 (Exp. VB1) and the soybean cultivar DK5520 (Exp. VB1, VC1, VR1 and VR2). For the traditional maize hybrid DK 615 data from 2 published field experiments (VB2 and VB3) were used (Izquierdo et al., 2009). All the experiments were conducted under non limiting conditions as described for the previous experiments. In Exp. VB1 the HO1 and HO2 maize hybrids were cultivated in Balcarce during the 2008–2009 growing season in a complete blocks design with three replications. During grain filling treatments to modify the radiation intercepted per plant were applied: (i) 80% shaded, (ii) 50% shaded, (iii) plant thinning (only in HO1) and (iv) control. The soybean cultivar DK 5520 was cultivated during the 2010–2011 growing season in Balcarce (VB1), Cordoba (VC1) and at Instituto Nacional de Tecnología Agropecuaria (INTA) Reconquista Experimental Station (29°11′S, 59°52′W), Argentina (VR1 and VR2) in plots with three replications. In VR1 two treatments were applied during grain filling: (i) 80% shade and (ii) control. No treatments were applied in VB1, BC1 and VR2. In VB2 and VB3 experiments the hybrid DK 615 was sown in Balcarce in a complete blocks design and treatments to modify the radiation intercepted per plant during grain filling were applied (Izquierdo et al., 2009). Further details about these experiments are shown in Table 3. In all the validation experiments oil fatty acid composition was determined at harvest after physiological maturity. Temperature and intercepted radiation per plant were measured and calculated as described for the other experiments.

2.4. Sample processing and chemical analysis

Oil fatty acid composition was determined in grains set at a similar date in order to avoid exposure to different environmental conditions during grain filling, as described by Izquierdo et al. (2009). Oil extraction and methylation was performed following the technique proposed by Sukhija and Palmquist (1988). Oil fatty acid composition was determined by gas–liquid chromatography (CGL, Varian 3400) and each fatty acid was expressed as a percentage of the total fatty acids identified in the oil. The oleic, linoleic, linolenic, palmitic and stearic acids were identified in all the samples.

3. Data analysis

The effect of ISR per plant on oil fatty acid composition was processed by analysis of variance procedures. Residuals of fatty acid concentrations were homogeneously distributed around zero so data were not transformed. When statistical differences were detected in more than one experiment or genotype, only the highest p value is presented. Differences between treatment means were evaluated with the Tukey test ($p < 0.05$). Data of oleic acid (or other fatty acids) percentages versus ISR per plant were adjusted to lineal and non lineal models. The models with the highest r^2 were always chosen. Sigmaplot software (Sigmaplot 8.0, SPSS Inc., Chicago, IL) was used to establish the relationships.

Data from control plots of the experiments RB1, RB2, RC1, RC2, RP1 and RP2 and from “temperature experiments” (Tgc and Tgh) were used to establish the relationships between oleic acid percentages and DMT. The effect of temperature on the oleic acid percentage was analyzed using linear functions. For the maize cultivar DK 615, data from growth chamber experiments conducted by Izquierdo et al. (2009) were also included in the data set used to establish the relationship between oleic acid (or other fatty acids) percentage and DMT.

A unique model between oleic acid percentage and ISR per plant and DMT during grain filling was fitted for each cultivar. Based on findings of Echarte et al. (2010) in sunflower and in general shape of measured oleic acid percentage data obtained at different ISR and DMT (see Section 4), these models consider that the effects of ISR per plant and DMT are additive. Adjustments were done by non lineal simple and multiple regressions using the Sigmaplot 8.0 software. The analysis of estimated oleic acid percentages versus data obtained in these experiments was used to verify the accuracy of the established relationship. A regression analysis was carried out and the hypotheses of intercept = 0 and slope = 1 were tested using IRENE (Integrated Resources for Evaluating Numerical Estimates, software beta version 1.00, Fila et al., 2003). The deviation between measured and estimated data was also evaluated by analyzing the components of the mean squared deviation (MSD) as proposed by Kobayashi and Salam (2000).

The established models were used to estimate the oleic acid percentage of the independent experiments VB1, VB2, VB3, VC1, VR1 and VR2. The hypothesis of intercept = 0 and slope = 1 for the regressions between observed and estimated data was tested with IRENE ($p \leq 0.05$).

4. Results

In experiments used to investigate and model the effect of ISR and DMT, oleic acid percentage varied among treatments and experiments between 42 and 70% in maize genotypes with increased oleic acid percentage and between 26 and 36% in the traditional genotype DK 615. In soybean, oleic acid percentages varied among treatments and experiments between 20 and 59% in genotypes with increased oleic acid percentage and between 17 and 26% in the traditional genotype DK 5520.

4.1. Effect of ISR per plant on oil fatty acid composition

Radiation treatments modified the oil fatty acid composition of all genotypes in RB and RC experiments. Shaded 80% reduced the oleic acid percentage as compared to the control in all the species and experiments ($p < 0.02$, Fig. 1). The oleic acid percentage of shaded showed an intermediate value between 80% shaded and the control in maize genotypes from RB2. Thinning treatment increased the oleic acid percentage as compared to the control in N98-4445A genotype from RB2. Differences in oleic acid percentage between extreme radiation treatments were higher in genotypes with increased oleic acid percentage of both species compared to traditional ones (mean difference across experiments = 8.0% versus 4.8% and 7.5 versus 2.7, oleic acid percentage points for maize and soybean, respectively).

Linoleic acid percentage varied among treatments and experiments between 26 and 41% in maize genotypes with increased oleic acid percentage and between 50 and 58% in traditional genotype DK 615. In soybean, linoleic acid percentages varied among treatments and experiments between 30 and 46% in genotypes with increased oleic acid percentage and between 52 and 58% in the traditional genotype DK 5520. Linoleic acid percentage in general increased with the decrease in ISR per plant, showing an inverse trend as compared to the oleic acid percentage. Shaded 80% plants increased the linoleic acid percentage in both species ($p \leq 0.0005$), except in the soybean genotype DK 5520 in RC2 ($p > 0.065$). Shaded 50% showed an intermediate value between 80% shaded and the control in maize genotypes from RB2. Differences in linoleic acid percentage between extreme radiation treatments were higher in HO genotypes compared to the traditional one (mean difference across experiments = 8.4% versus 4.3%, for HO genotypes and the traditional one, respectively). The same trend was observed in soybean (mean difference across experiments = 8.0% versus 2.0%, for increased oleic acid percentage and the traditional one, respectively).

Linolenic acid percentage varied among treatments and experiments up to 9 percentage points for any genotype. The concentration of this fatty acid was in general unaffected by radiation treatments in both species. The exception in maize was the traditional genotype DK 615 in RB2, where 80% presented a lower linolenic acid percentage than the thinning treatment (0.7% versus 1.0%). In soybean genotype M23 in all experiments and in DK 5520 in RC1 shaded treatments increased up to 2 percentage points the linolenic acid concentration respect to the control ($p < 0.010$).

Saturated fatty acids varied between extreme treatments less than 7 percentage points for any maize and soybean genotype. Palmitic and stearic acids were affected in a different way by radiation treatments during grain filling in both species. In maize, the palmitic acid percentage was not affected by radiation treatments, except in HO2 from RC1 where thinning treatment showed a lower palmitic acid percentage than shaded treatment ($p < 0.008$). Shaded treatments reduced the stearic acid percentage in maize genotypes ($p < 0.0227$) except in the traditional genotype in RC1 and RB1 experiments ($p > 0.6098$) where stearic acid percentage was not affected by radiation treatments. In soybean, shaded treatments reduced the palmitic acid percentage and increased the stearic acid percentage, except in N98-4445A and DK 5520 genotypes in RC2 where saturated fatty acids where unaffected by radiation treatments ($p > 0.1102$).

4.2. Relationship between ISR per plant and oil fatty acids concentrations

The oleic acid percentage was curvilinear and positively related to ISR per plant during grain filling in maize (Fig. 2). The oleic acid percentage was accounted for by ISR per plant by a unique relationship for each location (Balcarce and Cordoba) and genotype ($p \leq 0.0010$, $r^2 \geq 0.69$). No relationship was established for Pergamino because of the low number of data and the narrow variation in ISR per plant. For a given intercepted radiation level, the oleic acid percentage trend to be higher in Cordoba as compared to Balcarce in HO1 and HO2 genotypes. For a similar radiation level, the oleic acid percentage from RP1 and RP2 were higher than those for RB and RC in both genotypes (Fig. 2). In the traditional genotype of maize, positive and curvilinear relationships also accounted for the variation of oleic acid percentage in Balcarce or Córdoba ($p < 0.0001$, $r^2 \geq 0.69$, Fig. 2c). As observed for the high oleic genotypes, in the traditional genotypes the oleic acid percentages in Cordoba were higher than in Balcarce, at a similar level of ISR per plant.

ISR per plant also accounted for the variation of oleic acid percentage in the traditional genotype of soybean and the genotype with increased oleic acid percentage M23 ($p < 0.0001$, $r^2 \geq 0.71$, Fig. 2f). For the traditional genotype, a function for each location was fitted. The oleic acid percentage for a given intercepted radiation level was also higher in RC than in RB. For the M23 genotype, as data from both locations overlapped, a unique function was fitted (Fig. 2d). In N98-4445A genotype, tested only in RC2, a linear relationship was fitted between oleic acid percentage and ISR per plant during grain filling ($p < 0.0121$, $r^2 \geq 0.62$, Fig. 2e).

Linoleic acid percentage followed a curvilinear inverse relationship with ISR per plant in all the maize genotypes ($p \leq 0.001$, $r^2 \geq 0.61$, data not shown). In M23 and DK 5520 soybean genotypes, inverse and curvilinear relationships between linoleic acid percentage and ISR per plant were fitted. In N98-4445A (tested only in RC2) a linear inverse relationship was fitted between these two variables ($p \leq 0.01$, $r^2 \leq 0.64$, data not shown). In HO1 and HO2 genotypes and the traditional DK 615 (in RB2) the palmitic and stearic acid percentages were accounted for by the ISR per plant during grain filing ($p \leq 0.0292$, $r^2 \geq 0.57$, data not shown). Increasing ISR per plant linearly reduced the palmitic acid percentage and increased the stearic acid percentage in maize genotypes. In soybean, palmitic acid percentage was linearly and negatively related with ISR per plant, which accounted for 58% of the variation in this fatty acid ($p \leq 0.02$). Stearic acid percentage was linearly and positively related to ISR per plant during grain filing in soybean genotypes ($p \leq 0.02$, $r^2 \geq 0.75$).

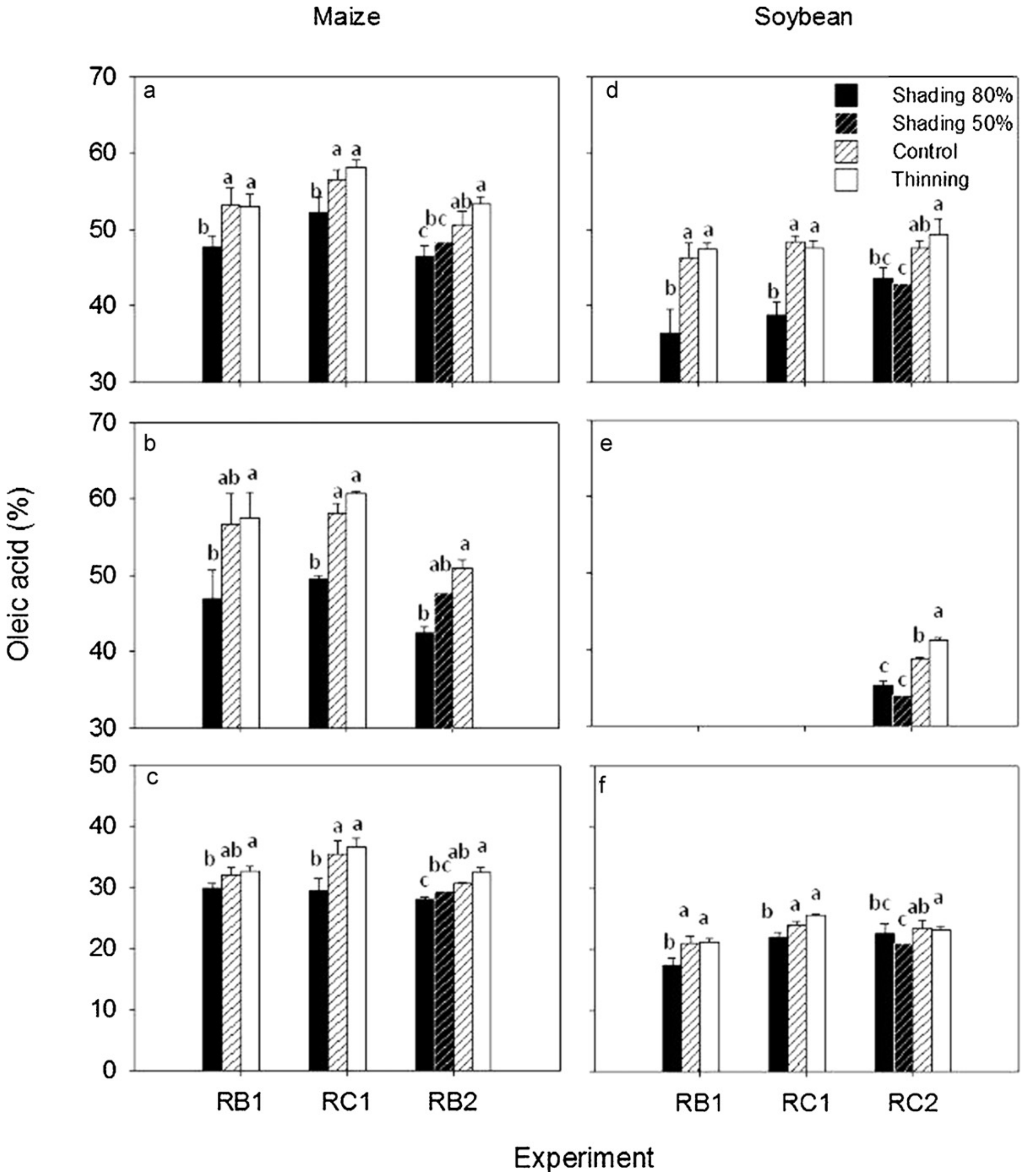

Fig. 1. Oleic acid percentage under different treatments of ISR per plant during grain filling for maize genotypes: (a) HO1, (b) HO2 and (c) DK 615 and soybean genotypes: (d) M23, (e) N98-4445A and (f) DK 5520 corresponding to RB1, RC1 and RB2 experiments. Vertical bars represent the standard deviation. For each genotype and experiment, different letters represent statistical differences among treatments (Tukey, $p < 0.05$).

4.3. Relationship between daily mean temperature and oil fatty acids concentrations

In maize, the oleic acid percentage varied from 40% to 70% (HO1 and HO2) and from 24% to 37% (DK 615) when data from Tgc, Tgh, the control treatments from field experiments and published data from Izquierdo et al. (2009) for the genotype DK 615 were considered together. DMT for this data set varied from 15 °C to 27 °C, approximately (Fig. 3). In the soybean genotypes N98-4445A and DK 5520, the oleic acid percentage varied from 20% to 50% and from 15% to 44%, respectively, as DMT varied from 12 °C to 27 °C, approximately. In M23, the oleic acid percentage varied from 46% to 59% and the range of DMT from 14 °C to 27 °C.

In both species, the oleic acid percentage was positively and linearly related to DMT ($p \leq 0.0352$, $r^2 \geq 0.41$, Fig. 3). In maize, the fitted equations for HO1 and HO2 genotypes showed similar slopes and intercepts ($p > 0.05$, Fig. 3). The slopes of the relationships fitted to data from HO1 and HO2 genotypes were higher than the slope of the relationship of the traditional genotype (2.33 and 2.29%/°C versus 0.62%/°C in HO1, HO2 and DK 615, respectively). In soybean, the slopes of the relationships were different among genotypes ($p < 0.001$, $r^2 \geq 0.41$, Fig. 3). The relationship between oleic acid percentage and DMT presented the lowest slope in M23 genotype, the highest slope in N98-4445A genotype and the traditional genotype presented an intermediate slope. In all genotypes and both species, data from oleic acid

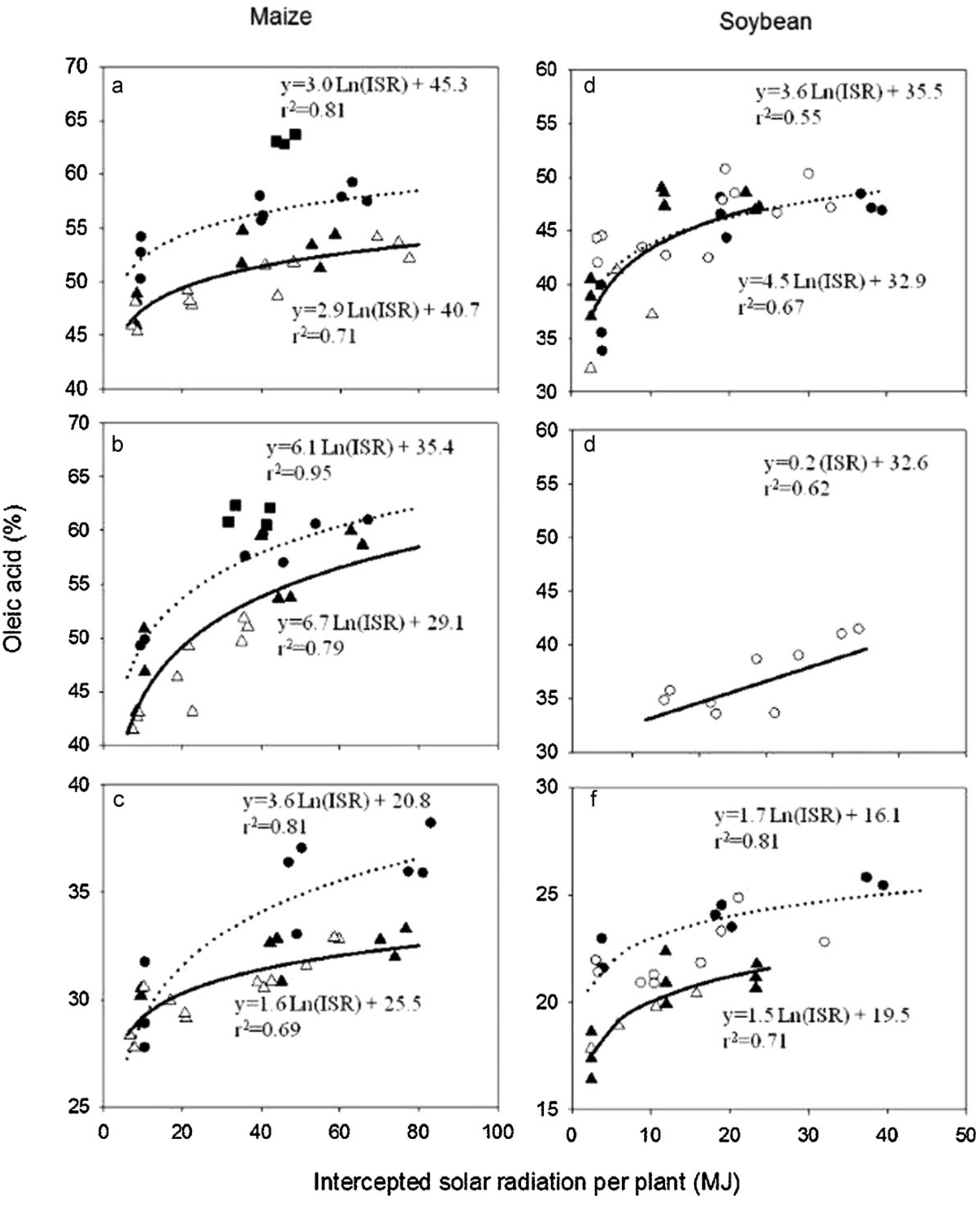

Fig. 2. Relationship between oleic acid percentage and ISR per plant (MJ) during grain filling of maize genotypes: (a) HO1, (b) HO2 and (c) DK 615 and soybean genotypes: (d) M23, (e) N98-4445A and (f) DK 5520. Data correspond to RC1 (●), RC2 (○), RB1 (▲), RB2 (△) and RP (■). Data from RP were not included in the relationships. In the equations, ISR is intercepted solar radiation per plant (MJ) during grain filling and y is oleic acid percentage.

percentage followed a similar trend with temperature irrespectively if they were obtained in the field, the greenhouse or the growth chambers making unlikely that variations in oleic acid percentage were produced by environmental conditions other than via DMT.

In all the maize genotypes, curvilinear inverse relationships were fitted between linoleic acid percentage and DMT during grain filling ($p \leq 0.001$, $r^2 \geq 0.63$, data not shown). In soybean genotypes, linear inverse relationships between linoleic acid percentage and DMT during grain filling were fitted ($p \leq 0.02$, $r^2 \geq 0.52$). In HO1 and HO2 genotypes and the traditional DK 615 the palmitic and stearic acid percentages were linearly accounted for by the DMT during grain filing ($p \leq 0.0292$, $r^2 \geq 0.57$, data not shown). In DK 5520 and N98-4445A soybean genotypes, palmitic acid percentage was not related to DMT during grain filling ($p \geq 0.06$) but the concentration of this fatty acid in M23 was linearly and positively related to DMT during grain filing ($p = 0.022$, $r^2 = 0.67$). Stearic acid percentage was not affected by DMT during grain filling in DK 5520 and N98-4445A soybean genotypes ($p \geq 0.4833$), except in M23 genotype. In this genotype the stearic acid percentage was linearly and

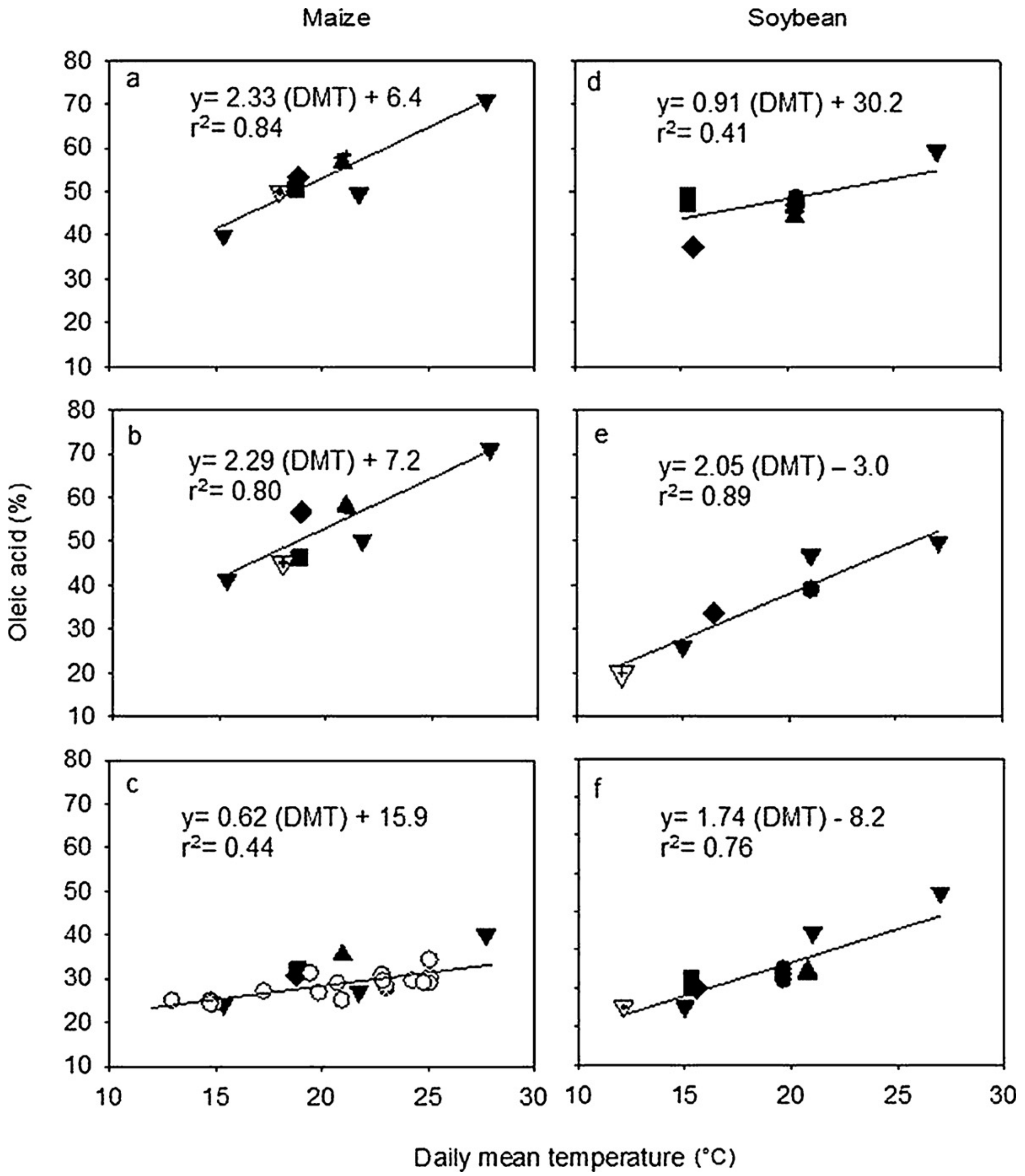

Fig. 3. Oleic acid percentage as a function of DMT during grain filling in maize genotypes: (a) HO1, (b) HO2 and (c) DK 615 and soybean genotypes: (d) M23, (e) N98-4445A and (f) DK 5520. Data correspond to RC1 (●), RC2 (○), RB1 (▲), RB2 (△), RP (■), Tgc (▼), Tgh (▽) and Izquierdo et al., 2009 (○). In the equations, DMT is daily mean temperature during grain filling and *y* is the oleic acid percentage.

negatively related to DMT during grain filing ($p = 0.002$, $r^2 = 0.75$, data not shown).

4.4. Oleic acid percentage as a function of ISR per plant and DMT

In the genotypes where different relationships between oleic acid percentage and ISR were established for each location (all maize genotypes and DK 5520 soybean genotype), a unique function pooling all data for each genotype accounted for between 58 and 76% of the variation in oleic acid percentage. The r^2 of these relationships were lower than the r^2 of the relationships presented in Fig. 2, established for each location separately. The residuals from the relationships obtained with the pooled data were linearly and inversely related with DMT in both species ($p \leq 0.0003$, data not shown). A relationship additively taking into account the effects of ISR and DMT on oleic acid percentage was then considered (Eq. (1)). The assumption of such additive effect of ISR and DMT on oleic acid percentage is based on results from Echarte et al. (2010) in a sunflower genotype and in the fact that for a similar radiation level, measured oleic acid percentage for each genotype presented in Fig. 2 trend to be higher when DMT during grain filling were higher (Pergamino > Cordoba > Balcarce, Table 2). Also, fittings presented in Fig. 2 for each genotype and location suggests an additive effect between ISR and DMT (note that DMT at RC experiments

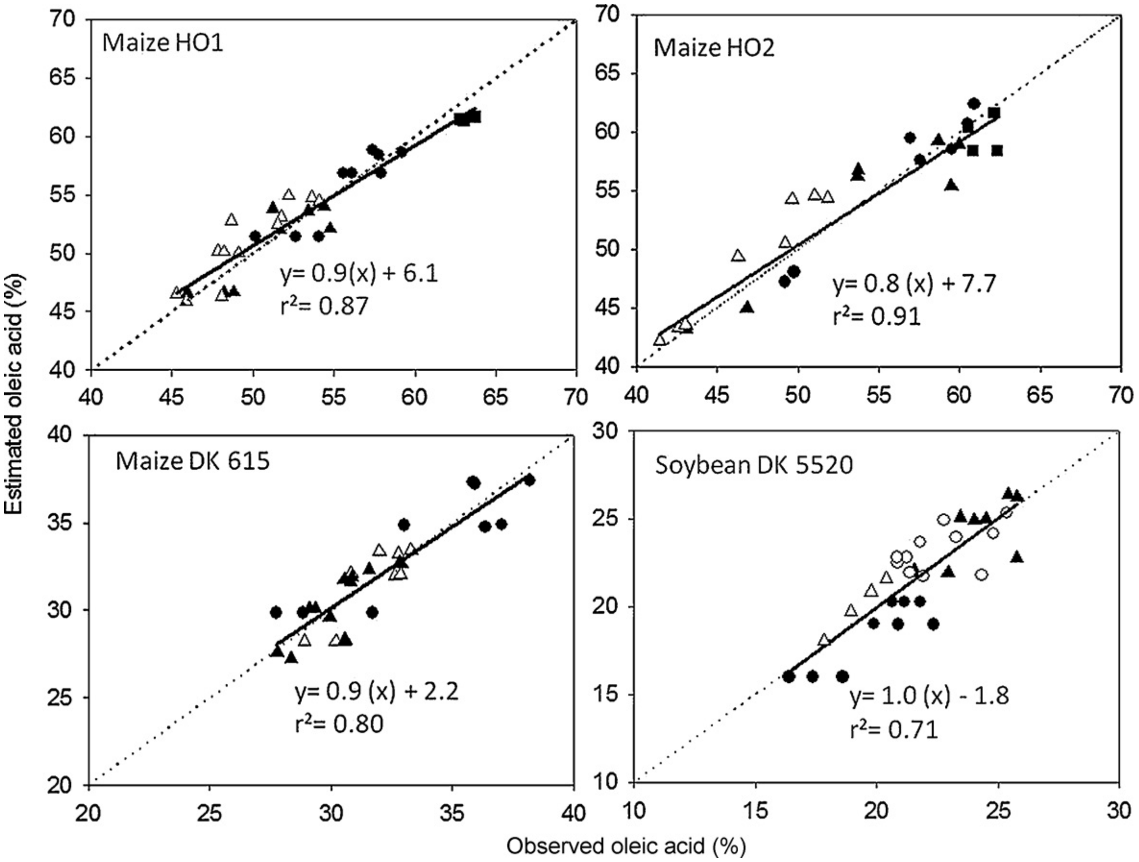

Fig. 4. Estimated versus observed oleic acid percentages for maize genotypes HO1, HO2 and DK 615 and soybean genotype DK 5520. Estimated data were obtained using Eq. (1). Data correspond to RC1 (●), RC2 (○), RB1 (▲), RB2 (△) and RP (■). Dotted lines represent the 1:1 relationship. Solid lines represent the lineal regression for data points.

where higher than in RB experiments in maize genotypes and in the traditional genotypes from soybean, Table 2):

$$[\text{Oleic acid}] = a\int(\text{ISR per plant}) + b\int(\text{DMT}) \qquad (1)$$

where ISR per plant is intercepted solar radiation per plant during grain filling, DMT is daily mean temperature during grain filling and a and b are parameters of the model.

For each genotype, the model including the effects of ISR per plant and DMT during grain filling ($p < 0.001$, Fig. 4 and Table 4) accounted for a higher proportion of the variation in oleic acid percentage among treatments and locations than the models considering the ISR per plant only (for example 92% versus 62% for HO1 genotype). The cloud of points from the different experiments overlapped when the estimated and observed data were plotted (Fig. 4). Data from RP experiments, which presented the highest oleic acid concentration (Fig. 2) were also well accounted for by this model. LCS was the major component of MSD ($\geq$84%), indicating that the model had neither a significant bias of the simulation from measurement (low SB) nor a lack or excess of sensitivity (low SDSD).

4.5. Validation experiments

Validation experiments included a wide range of daily mean temperature and intercepted solar radiation per plant during grain filling for the traditional cultivars DK 5520 (soybean) and DK 615 (maize) and the high oleic maize hybrids HO1 and HO2 (Table 3).

For the high oleic maize hybrids, when data were estimated using Eq. (1), including the additive effects of ISR per plant and daily mean temperature the slopes and intercepts were not different to 1 and 0, respectively (Fig. 5). Estimating data only with DMT (Fig. 3) presented a relationship between estimated and observed data with slope and intercept different from 1 and 0, respectively ($p < 0.006$). When data of VB1 were estimated with the relationships between oleic acid percentage and ISR per plant established for Balcarce (Fig. 2) the relationship between estimated and observed data presented slopes and intercepts not different from 1 and 0, respectively ($p < 0.0081$). Despite the range of DMT was lower than 2 °C in this experiment, the r^2 was increased when comparing the model considering ISR alone to the additive model considering both factors (from 0.74 to 0.80 and from 0.87 to 0.88 for HO1 and HO2, respectively). The slopes and intercepts were quantitatively closer to 1 and 0, respectively, when considering the additive model. For example, for HO2 when the model considering both effects was used the slope changed from 0.74 to 0.96 and the intercept changed from 13.45 to 1.49 compared to the model with ISR alone (data not shown).

In the traditional maize hybrid DK 615, two groups of data were observed for VB2 and VB3 (according to that previously reported by Izquierdo et al., 2009). The model considering an additive effect of ISR and DMT better predicted the experimental data than the models considering each factor alone. The relationship between predicted and observed data presented slopes and intercepts not different from 1 and 0 for both clouds of data (Fig. 5). When considering DMT alone, slopes and intercepts were different from 1 and 0, respectively ($p < 0.02$). When estimating VB3 experimental data based only in ISR per plant the relationship between estimated and observed data showed a slope and intercept different from 1 and 0, respectively. For VB2, estimating data with ISR per plant alone presented slopes and intercepts not different from 1 and 0, respectively ($p > 0.171$). The r^2 was lower compared to the

Table 4
Parameter values ± standard error, p value and r^2 for Eq. (1) (oleic acid percentage as a function of ISR per plant and DMT during grain filling) in maize genotypes HO1, HO2 and DK 615 and soybean genotype DK 5520.

	a	p	b	p	r^2
HO1	2.9 ± 0.3	<0.0001	2.2 ± 0.1	<0.0001	0.92
HO2	6.4 ± 0.7	<0.0001	1.6 ± 0.1	<0.0001	0.86
DK 615	1.9 ± 0.3	<0.0001	1.3 ± 0.05	<0.0001	0.81
DK 5520	1.8 ± 0.3	<0.0001	0.7 ± 0.04	<0.0001	0.73

additive model (0.56 versus 0.64). The relationship between observed and estimated data showed a slope quantitatively nearer to 1 (1.78 versus 1.35) and an intercept closer to 0 (26.6 versus 9.5) for the additive model compared to the model taking in account the ISR alone.

For the traditional soybean cultivar DK 5520 estimating data with ISR per plant only or DMT alone presented relationships between estimated and observed data with slopes and intercept different from 1 and 0, respectively. The model considering the additive effects of ISR per plant and DMT well estimated (r^2 = 0.98) the oleic acid percentage of VB1, VC1, VR1 and VR2 experiments. When using the additive model, the relationship between estimated and observed data presented a slope and intercept not different from 1.0 and 0, respectively (Fig. 5).

5. Discussion

Comparative sensitivity of traditional and increased oleic acid percentage genotypes of soybean and maize to temperature and intercepted solar radiation.

The effects of changes in DMT and ISR per plant during grain filling on the oil fatty acid composition of maize and soybean genotypes with increased oleic acid percentage were assessed in this work. No studies about these effects had been previously performed

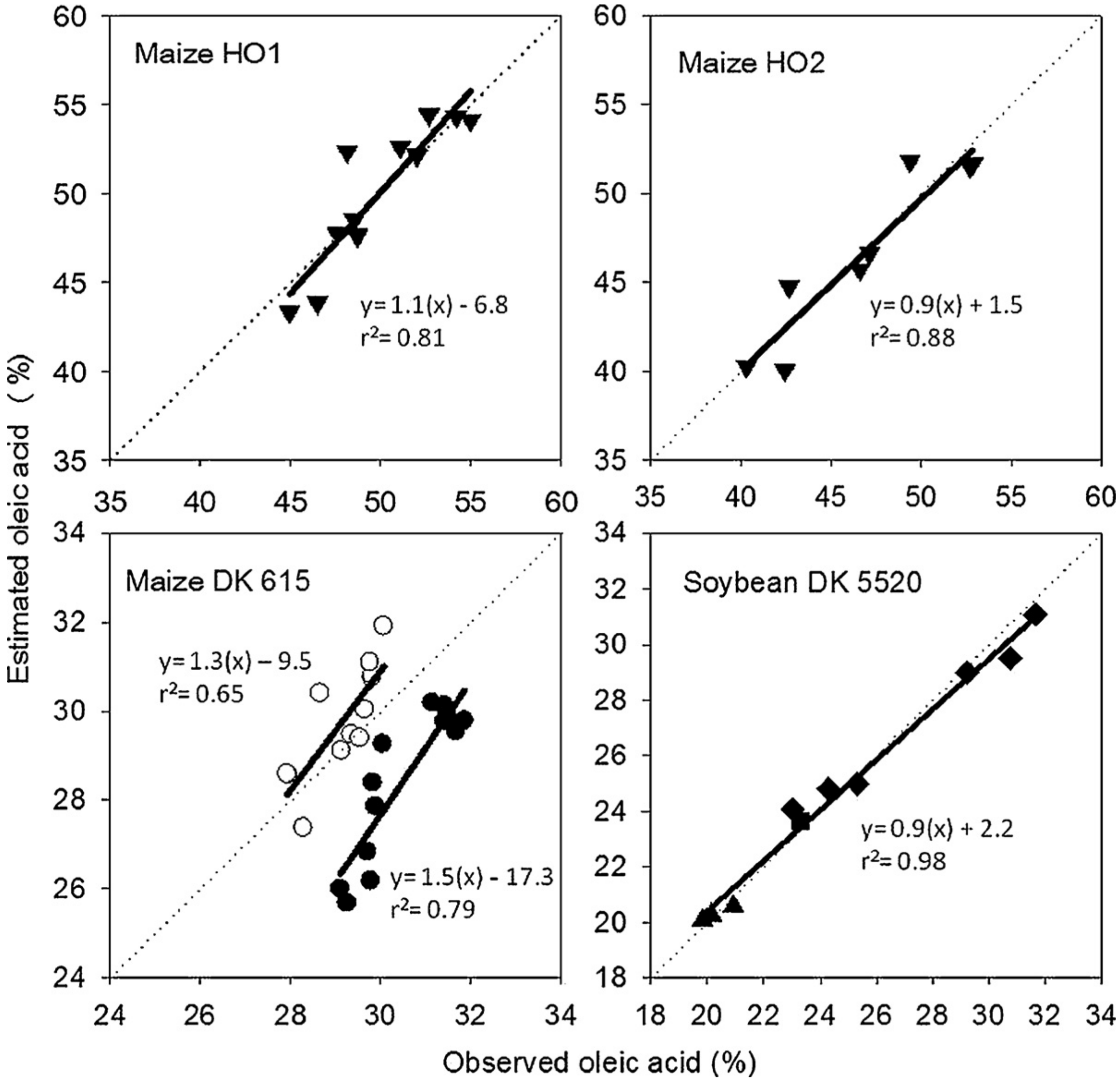

Fig. 5. Estimated versus observed oleic acid percentages from validation experiment for maize genotypes HO1, HO2 and DK 615 and soybean genotype DK 5520. Estimated data were obtained using Eq. (1). Data correspond to VB1 (▼), VB2 (○), VB3 (●), VB1 (▲), VC1 (■), VR1 (♦), VR1 (◊). Dotted lines represent the 1:1 relationship. Solid lines represent the lineal regression for data points.

in this kind of genotypes. In soybean, a few works about the effects of DMT on oleic acid percentage have been reported (Izquierdo et al., 2009; Oliva et al., 2006) but the effect of ISR per plant has not been previously investigated in genotypes with increased oleic acid percentage. Moreover, the relative sensitivity to ISR of genotypes with increased oleic acid percentage respect to traditional genotypes was unknown. Oil fatty acid composition of most of the tested genotypes with increased oleic acid percentage of maize and soybean was more affected by ISR per plant and DMT than in traditional ones. The only exception was the M23 soybean genotype which showed a lowest slope than the traditional one in response to DMT. This higher sensitivity of most of the genotypes with increased oleic acid percentage was unexpected as in other species, oil fatty acid composition of genotypes with increased oleic acid percentage was less affected by environmental conditions than traditional ones (e.g. Schierholt and Becker, 2001 in rape; Triboi-Blondel et al., 2000 in sunflower). So, based on these results the hypothesis proposed in the introduction section is rejected.

5.1. Response of oleic acid percentage to intercepted solar radiation per plant during grain filling

In traditional genotypes of maize, soybean and sunflower, Izquierdo et al. (2009) found a linear relationship between oleic acid percentage and ISR per plant. In this work, increasing ISR per plant also increased the oleic acid percentage, but the relationships between these variables were curvilinear. This pattern of response observed in maize and soybean genotypes agree with that reported for sunflower by Echarte et al. (2010). This pattern where the oleic acid percentage saturates at high levels of ISR per plant was observed even in traditional and high oleic genotypes. Saturating responses at high ISR per plant have been also reported for grain weight and/or oil concentration in sunflower (e.g. Dosio et al., 2000). When ISR per plant is reduced, the supply of assimilates to the grains decreases and causes a lower weight per grain and grain oil concentration, but with higher levels of ISR per plant the capacity to accumulate dry matter in grain tissues was saturated in some genotypes. Echarte et al. (2010) proposed that at high irradiances, the oleate desaturase enzyme, responsible of the desaturation of oleic to linoleic acid, would be substrate saturated and thus increased carbon availability would lead to a relative accumulation of oleic acid.

5.2. Response of oleic acid percentage to temperature during grain filling

Increasing DMT linearly increased the oleic acid percentage in both traditional and high oleic genotypes of maize and soybean. This effect explains why, for a given ISR per plant level, oleic acid concentration followed a direct trend with the temperature registered in the locations where experiments were performed (Pergamino > Córdoba > Balcarce). Linear responses of oleic acid percentage to DMT were also observed by Izquierdo et al. (2009) in traditional genotypes of both species. In several sunflower traditional genotypes and one high oleic genotype, sigmoid relationships were observed between the oleic acid percentage and temperature (Izquierdo and Aguirrezábal, 2008). These authors suggested that the values of the plateaux at low and high temperatures would reflect the maximum and minimum activity of the oleate desaturase enzyme. Probably, the relationship between oleic acid percentage and DMT in soybean and maize is also sigmoid as in sunflower but the temperatures, above and below which the concentration of oleic acid remains relatively constant, are lower and higher than those explored in this work. This could be interesting to investigate in the view to increase the current knowledge about the mechanisms involved in the synthesis of oil fatty acids in soybean and maize. However, the range of temperature explored in this work seems large enough for soybean and maize from an agronomic point of view to apply in crop management and modeling as it represents the DMT during grain filling in the sowing area of these species around the world.

Oliva et al. (2006) reported that temperature during grain filling did not affect the oleic acid percentage in the M23 genotype. In this work, increasing DMT increased the oleic acid percentage in this genotype. These different responses found in both works may be due to the effect of other environmental factors that were not controlled in their experiments (e.g. water availability), while data presented in this work were obtained under no limiting conditions. Despite of the significant effect of temperature on oleic acid percentage in M23, this genotype presented the lowest sensitivity to this environmental factor. On the opposite, the oleic acid composition of N98-4445A genotype was the most sensitive when the plants were subjected to different temperatures during grain filling. Genetic variability in the genes involved in the increase of oleic acid percentage could be at the basis of the different sensitivity of oil fatty acid composition of both genotypes to temperature. The inheritance of the increase oleic acid concentration in M23 genotype is determined by one gene (Takagi and Rahman, 1996) where the *ol* allele gene decreases the desaturation of oleic acid (Alt et al., 2005). Consistently, in high oleic genotypes of sunflower, which show a low sensitivity to temperature, the oleic acid percentage is determined by three allelic genes (Ol_1, Ol_2 and Ol_3, Demurin et al., 2000). In sunflower, other several minor genes with small effect (often called “modifiers”) are involved in the increased oleic acid concentration and its stability (Fernández-Martínez et al., 2004). The soybean genotype N98-4445A has several minor genes that codify for the oleic acid percentage (Oliva et al., 2006). Primomo et al. (2002) suggested that genotypes where the expression of a higher oleic acid percentage depends on several minor genes (e.g. N98-4445A genotype) show a higher sensitivity to environmental factors than genotypes with a low number of genes codifying for the oleic acid content (e.g. M23 genotype). Further investigations must been performed to investigate the genetic basis of the higher stability of oleic acid percentage in response to temperature variations as in this work M23 was the only genotype with increased acid composition which showed a lower sensitivity to temperature than the traditional tester.

In maize, the response of oleic acid percentage to DMT during grain filling was similar in both studied genotypes with increased oleic acid percentage. However, these genotypes presented different response of oleic acid percentage to ISR per plant. This data suggest that genetic variability in the response of fatty acid composition to ISR per plant could exist in maize, even between genotypes with increased oleic acid concentration. To further assess this genetic variability in the response of oleic acid percentage to ISR more genotypes should be investigated. In soybean, differences were found in the response of oleic acid percentage to ISR per plant and DMT during grain filling in genotypes with increased oleic acid percentage suggesting also genetic variability for this trait.

5.3. Additivity of the effects of temperature and intercepted solar radiation on oleic acid percentage

According to the data presented in this work, the effects of DMT and ISR per plant during grain filling on the oleic acid percentage of genotypes with increased oleic acid percentage of soybean and maize are additive. When the established models were tested with an independent data set, the models considering additivity between DMT and ISR effects on oleic acid percentage well predicted the observed data. They improve in most of cases (4 of 5 cases) the prediction of oleic acid percentage compared to the prediction based on DMT or ISR alone. The prediction of experimental independent data was specially improved for the soybean genotype DK5520, the cultivar which was tested under the wider range of DMT combined with a wide ISR variation. Echarte et al. (2010) also reported additivity of these two effects on the oleic acid percentage *n* a traditional sunflower genotype. Different sensitivity of genotypes to ISR and DMT (e.g. oil oleic acid percentage presented a low sensitivity to DMT and a high sensitivity to ISR in M23 genotype) also support the idea that both are independent effects. The results presented in this work suggest that these independent effects are common to different genotypes of maize and soybean. Also, these effects are also common in genotypes with mutations that modify its oil fatty acid synthesis as those with increased oleic acid percentage.

Crop simulation models are a valuable tool for analyzing variability and complex interactions with low cost and in a short time. Cultural practices could be used to manage the oil fatty acid composition by taking into account the genotype potential and the environmental conditions during grain filling. For example, in some regions, early sowing dates are known to lead to higher yields (in potential conditions) but they also can result in lower oleic acid percentage in maize and soybean genotypes. Many models that predict development and yield have been developed in several crops including soybean and maize (Herrmann et al., 2005; Stöckle et al., 2003). Our results could be integrated to these crops models or new ones for selecting the best location, sowing date and sowing density for the production of a specific grain or oil quality with highest yield.

6. Conclusions

In maize and soybean genotypes with increased oleic acid percentage, intercepted solar radiation per plant and daily mean temperature during grain filling affected the oil fatty acid composition. Increasing daily mean temperature and/or intercepted solar radiation per plant (up to a saturation level) increased the oleic acid percentage at the expense of linoleic and/or linolenic acid percentage. Intercepted solar radiation per plant and daily mean temperature during grain filling independently affect oleic acid percentage of genotypes with increased oleic acid percentage in both species. Based on these results, management practices that increase temperature and per plant intercepted solar radiation during grain filling (e.g. sowing date, location, fertilization) could help to obtain soybean and maize oils with higher oleic acid percentage even in traditional or increased oleic acid genotypes.

Acknowledgements

This work was supported by the Instituto Nacional de Tecnología Agropecuaria (INTA) PNCER 02345, 2006–2008 and PNCER 024022, 2009–2011, Agencia Nacional de Promoción Científica y Tecnológica PICT 941, 2010–2012 and Universidad Nacional de Mar del Plata (UNMdP). Results were taken from Sebastián Zuil and Jorge Lujan M.S. Thesis (Universidad Nacional de Mar del Plata and Universidad Nacional de Córdoba). Authors wish to thank Dr. Alfredo Cirilo for his valuable collaboration in Pergamino Experiments and Luis Mendez (INTA-EEA Balcarce) for technical assistance.

References

Alt, J.L., Fehr, W.R., Welke, G.A., Sandhu, D., 2005. Phenotypic and molecular analysis of oleate content in the mutant soybean line M23. Crop Sci. 45, 1997–2000.

Andrade, F., Echeverría, H., González, N., Uhart, S., 2000. Requerimientos de nutrientes minerales. In: Andrade, F., Sadras, V. (Eds.), Bases Para el Manejo del Maíz. el Girasol y la Soja, Argentina, 443 pp.

Demurin, Y., Škoric, D., Verešbaranji, I., Jocic, S., 2000. Inheritance of increased oleic acid content in sunflower seed oil. Helia 23, 87–92.

Dosio, G.A.A., Aguirrezábal, L.A.N., Andrade, F.H., Pereyra, V.R., 2000. Solar radiation intercepted during seed filling and oil production in two sunflower hybrids. Crop Sci. 40, 1637–1644.

Durrett, T.P., Benning, C., Ohlgrogge, J., 2008. Plant triacylglycerols as feedstocks for the production of biofuels. Plant J. 54, 593–607.

Echarte, M.M., Angeloni, P., Jaimes, F., Tognetti, J., Izquierdo, N.G., Valentinuz, O., Aguirrezábal, L.A.N., 2010. Night temperature and intercepted solar radiation additively contribute to oleic acid percentage in sunflower oil. Field Crops Res. 119, 27–35.

Erkkila, A., Mello, V.D.F., Risérus, U., Laaksonen, D.E., 2008. Dietary fatty acid and cardiovascular disease: An epidemiological approach. Prog. Lipid Res. 47, 172–187.

Fehr, W.R., Cavinness, C.E., 1977. Stages of soybean development. Cooperative Extension Service Special Report No. 80. Iowa Agric. Exp. Sta. Ames, IA. 11 pp.

Fernández-Martínez, J.M., Velasco, L., Pérez-Vich, B., 2004. Progress in the genetic modification of sunflower quality. In: Proceedings 16th International Sunflower Conference, Vol. I, Fargo, ND, USA, International Sunflower Association, pp. 1–14.

Fila, G., Bellochi, M., Donatelli, M., Acutis, G., 2003. IRENE_DLL: a software to evaluate model performance. Eur. J. Agron. 18, 369–372.

Gallo, K.P., Daughtry, C.S.T., 1986. Techniques for measuring intercepted and absorbed photosynthetically active radiation in corn canopies. Agron. J. 78, 752–756.

Herrmann, A., Kornher, A., Taube, F., 2005. A new harvest time prognosis tool for forage maize production in Germany. Agric. Forest Meteorol. 130, 95–111.

Izquierdo, N.G., Aguirrezábal, L.A.N., 2008. Genetic variability of the response of fatty acid composition to temperature. Field Crops Res. 106, 116–125.

Izquierdo, N.G., Aguirrezábal, L.A.N., Andrade, F.H., Geroudet, C., Valentinuz, O., Pereyra Iraola, M., 2009. Intercepted solar radiation affects oil fatty acid composition in crop species. Field Crops Res. 114, 66–74.

Kane, M.V., Steele, C.C., Grabau, L.J., MacKown, C.T., Hildebrand, D.F., 1997. Early maturing soybean cropping system. 3. Protein and oil contents and oil composition. Agron. J. 89, 464–469.

Kobayashi, K., Salam, M., 2000. Comparing simulated and measured values using mean squared deviation and its components. Agron. J. 92, 345–352.

Mensink, R.P., Katan, M.B., 1989. Effect of a diet enriched with monounsaturated or polyunsaturated fatty acids on levels of low-density lipoprotein cholesterol in healthy women and men. N. Eng. J. Med. 321, 436–441.

Oliva, M.L., Shannon, J.G., Sleper, D.A., Ellersieck, M.R., Cardinal, A.J., Paris, R.L., Lee, J.D., 2006. Stability of fatty acid profile in soybean genotypes with modified seed oil composition. Crop Sci. 46, 2069–2075.

Primomo, V.S., Falk, D.E., Ablett, G.R., Tanner, J.W., Rajcan, I., 2002. Genotype × environment interactions, stability and agronomic performance of soybean with altered fatty acid profiles. Crop Sci. 42, 37–44.

Ritchie, S.W., Hanway, J.J., Benson, G.O., 1997. How a corn plant develops. Special Report No. 48. Iowa State University of Science and technology, Cooperative Extension Service Ames, Iowa. 21 pp.

Schierholt, H., Becker, C., 2001. Environmental variability and heritability of high oleic acid content in winter oilseed rape. Plant Breeding 120, 63–66.

Stöckle, C., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18, 289–307.

Strecker, L.R., Bieber, M., Maza, A., Grossberger, T., Doskoczynski, W.J., 1997. Aceite de maíz. Antecedentes, composición, procesamiento, refinación, utilización y aspectos nutricionales. Aceites y Grasas 507, 527.

Sukhija, P.S., Palmquist, D.L., 1988. Rapid method for determination of total fatty acid content and composition of feedstuffs and feces. J. Agric. Food Chem. 36, 1202–1206.

Takagi, Y., Rahman, S.M., 1996. Inheritance of high oleic acid content in the seed oil of soybean mutant M23. Theor. Appl. Genet. 92, 179–182.

Triboi-Blondel, A., Bonnemoy, B., Falcimagne, R., Martignac, M., Messaoud, J., Philippon, J., Vear, F., 2000. The effect of temperature from flowering to maturity on seed composition of high oleic sunflower inbreeds and mid oleic hybrids. In: Proceedings of the 15th International Sunflower Conference, Vol. I, Toulouse, France, p. A-67.