Quantifying factors determining seed weight in open pollinated and hybrid oilseed rape (*Brassica napus* L.) cultivars

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Abstract

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Seed weight (SW) in oilseed rape (*Brassica napus* L.) is determined during the seed filling period (SFP). A great proportion of variation in SW is associated with environmental conditions in this period. To quantify factors determining SW in open pollinated (OP) and hybrid cultivars of oilseed rape, 12 field experiments were conducted at Agricultural Research Station of Gonbad, Iran, during 2000-07 growing seasons. The experiments were often carried out under optimal growing conditions. Results clearly showed the importance of air temperature in determining the duration of the SFP, and consequently SW. The SW was maximized for the cultivars when exposed to the lower temperatures during the SFP. The ability of cultivars to produce photosynthetic assimilates for developing seeds was an effective determinant factor for SW. The relationships between SW with leaf area index (LAI) and aboveground dry matter, (ADM) at the onset of SFP, was positive and strong, showing a greater response of hybrid cultivars to increase in LAI and ADM as compared to OPs. In both groups, temperature and radiation interactions during SFP, as showed by photo-thermal quotient (PTQ), reasonably explained variation in SW. Therefore, further increase in seed yield (SY) through increasing SW could be obtained by improvement in one or a combination of these environmental factors as well as crop characteristics. These relationships are simple tools that could be applied to simulation models of SW in oilseed rape.

Key words: Seed number, Photo-thermal quotient (PTQ), Seed yield, Assimilate supply and Temperature.

Introduction

Oilseed rape (*Brassica napus* L.) is an important oilseed crop in Gonbad area, Iran. The acreage of oilseed rape in this area, where this crop has not been traditionally grown is increasing due to increased awareness of its benefits in crop rotations. In oilseed rape, final seed yield (SY) is determined primarily by seed number (SN) per unit area (Morison, 1993; Brandt and McGregor, 1997; Angadi *et al.*, 2000), however, variation in seed weight (SW) does also affect SY. Factors such as sowing date (Adamsen and Coffelt, 2005), soil moisture (Gan *et al.*, 2004), assimilate availability (Habekotte, 1993), and temperature (Morrison and Stewart, 2002; Johnson *et al.*, 1995) affect seed development, limiting the achievement of maximum SW. SW in oilseed rape is determined during the SFP and a great proportion of the variation in SW is related to environmental conditions during this period (Saini and Westgate, 2000). Therefore, direct selection for longer SFP may increase yield, and conversely, selection for higher yield in many cultivars may result in longer SFP (Egli, 2004). However, extending SFP of oilseed rape may be the most promising avenue to higher yields.

Oilseed rape leaves are an important source of photosynthates, even though they senesce rapidly during SFP (Chongo and McVetty, 2001). Leaves establish the sink potential in terms of structures such as number of pods per plant or number of seeds per pod, and as a source of remobilized assimilate during their senescence (Chapman *et al.*, 1984). SW is regulated by the ability of leaves to supply assimilates to the developing seeds, and the ability of the seeds to use this assimilates for continued growth. However, water and high temperature stresses during SFP accelerate leaf senescence and shorten the SFP (Dosio *et al.*, 2000). The mechanism by which assimilate availability might regulate oilseed rape seed development and weight have not been clearly established yet, and less information is available about the effect of environmental conditions during SFP on SW. Moreover, there are differences in patterns of reproductive growth between open pollinated (OP) and hybrid cultivars in oilseed rape (Faraji *et al.*, 2009). Therefore, understanding of the SW response of OP and hybrid cultivars to environmental conditions during SFP as well as assimilate supply at the onset of SFP will facilitate making management decisions.

The objective of this study was to quantify the environmental factors and crop attributes determining SW in OP and hybrid cultivars in oilseed rape.

Materials and Methods

To quantify factors determining SW in OP and hybrid cultivars of oilseed rape (Table 1), 12 field experiments were conducted at Agricultural Research Station of Gonbad; 45 m asl, 37^{o} 15' N and 55^{o} 10' E, Golestan province, Iran, during 2000-07 growing seasons (Table 2).

Table 1. Names of open pollinated and hybrid cultivars used during 2000-07 growing seasons

	Open pollinated	Hybrid
Experiment 1	Legacy, Syn-2, Syn-3, Cyclon, Noresman, Kristina, Profit, LG3310, Garrison, Magnum, Balero, Rafaela, Sponsor, Dakini, Fusia, Foseto, Shiralee, Quantum, Goliath, Sarigol, Option500	Hyola308, Hyola401
Experiment 2	Sarigol	Hyola401
Experiment 3	Sarigol	Hyola401
Experiment 4	Sarigol	Hyola401
Experiment 5	Quantum	-
Experiment 6	Sarigol, Goliath, Heros, Comet, Amica, SW5001, Cracker jack, Eagle, Wild cat, SW hot shot, Olega, 19-H, Syn-3, Option 500	Hyola401 (Foreign), Hyola401 (Safiabad), Hyola401 (Borazjan), Hyola420
Experiment 7	Syn-3, Option 500	-
Experiment 8	Option500, Quantum, Syn-3	Hyola401
Experiment 9	RGS003	-
Experiment 10	Comet, Amica, Magent, Alexandra, Foseto	-
Experiment 11	RGS003, Amica, Sarigol, Option500, Kimberly, RGS006, Syn-3, PR-401/16, PP-401/15E, PP-308/8, PP-308-3	Hyola401, Hyola60, Hyola420, Hyola330, Hyola308
Experiment 12	RGS003	Hyola401

Table 2. Summary of treatments and measurements in 12 experiments carried out during 2000-07 growing seasons

	Growing season	Treatments and cultivars	Measurements
Experiment 1	2000-2002	Yield trail (21 OP and 2 hybrid cultivars)	Phenology, SN, SW, SY
Experiment 2	2000-2002	Four sowing dates, 2 row spacing and 2 cultivars (1 OP and 1 hybrid)	Phenology, SN, SW, SY
Experiment 3	2001-2002	Three irrigation regimes, 3 nitrogen amounts and 2 cultivars (1 OP and 1 hybrid)	Phenology, SN, SW, SY
Experiment 4	2001-2002	Nine fertilizer treatments and 2 cultivars (1 OP and 1 hybrid)	Phenology, SN, SW, SY
Experiment 5	2001-2003	Three seed rates, 3 row spacing (1 OP Cultivar)	Phenology, SN, SW, SY
Experiment 6	2002-2004	Yield trail (14 OP and 4 hybrid cultivars)	Phenology, SN, SW, SY
Experiment 7	2002-2004	Three seed rates, 3 row spacing and 2 cultivars (1 OP and 1 hybrid)	Phenology, SN, SW, SY
Experiment 8	2002-2004	Four sowing dates and 4 cultivars (3 OP and 1 hybrid)	Phenology, SN, SW, SY
Experiment 9	2003-2005	Three sowing dates, 3 row spacing (1 OP Cultivar)	Phenology, SN, SW, SY
Experiment 10	2003-2006	Yield trail (5 OP cultivars)	Phenology, SN, SW, SY
Experiment 11	2004-2006	Yield trail (11 OP and 5 hybrid cultivars)	Phenology, SN, SW, SY
Experiment 12	2005-2007	Five sowing dates, 2 irrigation regimes and 2 cultivars (1 OP and 1 hybrid)	Phenology, SN, SW, SY, ADM, LAI

SN: seed number; SW: seed weight; SY: seed yield; OP: open pollinated. All cultivars used were spring type *B. napus*.

The experiments were carried out at different sowing dates, usually under optimal growing conditions with adequate supply of nutrients in pest, disease and weed-free environments. The region is classified as a warm and semi-arid Mediterranean climate. The soil was a fine, silty, mixed, thermic typic Calcixerol. Prior to sowing, soil samples were taken, and based on soil test, adequate N, P and K fertilizers were applied from urea, triple super phosphate and potassium sulphate sources, respectively. After seedling establishment, plants were thinned to desired spacing. Experimental Plots were hand weeded regularly.

Phenological stages were recorded following Harper and Berkenkamp (1975). Above dry matter (ADM) and leaf area index (LAI) were taken from 10 plants. Leaf area was measured using a leaf-area meter (DIAS, Delta-T Devices). At physiological maturity, 10 plants were sampled from each plot to determine SN m^{-2} (plant density m^{-2} × pod number per plant × SN per pod). A 1000-seed sample was weighed (with 8% moisture content) to determine SW. Names of cultivars, summary of some treatments and measurements in each experiment are presented in Table 1 and 2, respectively. Weather data recorded at a nearby weather station (Table 3). Photo-thermal quotient (PTQ) was calculated as the ratio of mean daily incident radiation to mean daily temperature in excess of 0 °C (Adamsen and Coffelt, 2005; Poggio *et al.,* 2005). Mean temperature and PTQ were calculated as the sum of daily temperatures and PTQs divided by the number of days of SFP. For LAI and ADM, only the data of a two year experiment was used for regression analysis (Table 1), since there was not enough reliable data in the other experiments. The regression models were fitted into the data of each group of cultivars, over years, experiments and sowing dates-using SAS software (SAS Institute Inc., 1996).

Results

Seed weight (SW) was affected by the duration of SFP, and SW was maximized when plants of both groups of cultivars experienced lower temperatures in this period (Fig 1 and Fig 2).

The relationship between SW and the duration of SFP was strong, explaining 70% and 77% of the variation in SW for OP and hybrid cultivars, respectively (Fig. 1). For each day increase in the duration of SFP, SW of OP and hybrid cultivars increased by 0.067 and 0.075 mg, respectively (Fig. 1).

Table 3. Monthly meteorological data at Gonbad Agricultural Research Station during 2000-2007 growing seasons.

Years		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
2000-01	Tmax (^{0}C)	23.9	17.9	15.7	12.4	17.0	20.4	24.2	31.7	34.4
	Tmin (^{0}C)	13.7	7.3	6.3	3.1	3.7	7.3	11.8	16.2	20.9
	Precipitation (mm)	29.8	9.0	57.6	11.0	32.8	77.0	11.3	14.2	1.7
	Rad. (MJm^{-2}day^{-1})	8.9	6.2	5.4	5.5	8.9	10.1	12.1	14.2	15.2
	Evap. (mm day^{-1})	2.8	1.9	1.3	1.1	1.7	2.4	3.4	5.5	6.6
2001-02	Tmax (^{0}C)	26.0	20.5	18.2	13.0	16.1	20.4	20.5	26.8	33.6
	Tmin (^{0}C)	13.2	9.8	6.1	3.5	4.1	7.3	10.5	14.1	19.3
	Precipitation (mm)	6.3	35.8	14.0	51.9	23.7	31.6	109.9	12.6	25.4
	Rad. (MJm^{-2}day^{-1})	10.0	7.3	5.4	5.7	8.0	9.9	10.4	13.8	15.9
	Evap. (mm day^{-1})	3.5	2.3	1.7	1.0	1.4	2.4	2.1	3.9	6.9
2002-03	Tmax (^{0}C)	29.8	20.1	11.3	13.6	12.9	13.9	18.6	27.7	31.8
	Tmin (^{0}C)	16.7	9.3	1.3	3.7	4.5	5.2	9.0	13.0	17.7
	Precipitation (mm)	33.8	60.7	55.2	28.3	57.6	89.0	75.5	35.6	8.5
	Rad. (MJm^{-2}day^{-1})	9.3	6.5	5.4	5.5	6.3	8.1	9.2	16.4	15.7
	Evap. (mm day^{-1})	3.5	1.1	0.8	1.3	1.3	1.4	1.6	4.3	6.0
2003-04	Tmax (^{0}C)	30.0	19.4	15.8	20.8	19.4	19.5	21.7	28.1	33.8
	Tmin (^{0}C)	15.8	8.2	6.9	8.8	8.2	7.7	8.9	15.5	20.3
	Precipitation (mm)	28.6	85.4	43.2	5.0	85.4	40.9	101.1	34.1	14.6
	Rad. (MJm^{-2}day^{-1})	9.4	6.4	5.1	6.0	7.6	10.4	11.8	14.2	16.6
	Evap. (mm day^{-1})	3.1	1.8	2.0	2.6	1.8	2.6	2.8	4.7	6.4
2004-05	Tmax (^{0}C)	27.0	21.0	12.9	12.3	12.4	18.1	22.9	28.8	33.5
	Tmin (^{0}C)	12.8	10.0	3.7	3.5	2.4	7.6	10.2	15.8	20.4
	Precipitation (mm)	66.3	80.8	58.4	66.2	47.7	49.2	22.1	64.9	18.0
	Rad. (MJm^{-2}day^{-1})	9.7	6.5	5.3	6.0	7.7	9.2	12.6	14.8	14.8
	Evap. (mm day^{-1})	2.9	1.6	0.9	1.1	1.7	1.9	2.9	4.7	5.4
2005-06	Tmax (^{0}C)	27.6	18.8	16.7	10.2	16.5	19.3	23.4	29.7	37.5
	Tmin (^{0}C)	14.7	7.8	6.1	0.5	4.4	6.9	11.8	15.9	21.9
	Precipitation (mm)	29.9	139.3	36.7	47.3	34.5	22.6	52.8	22.3	8.1
	Rad. (MJm^{-2}day^{-1})	9.6	6.3	5.5	6.0	8.1	9.9	11.6	13.6	17.1
	Evap. (mm day^{-1})	3.1	1.7	1.1	1.0	1.5	2.2	2.9	4.1	7.6
2006-07	Tmax (^{0}C)	29.3	19.4	12.1	15.9	15.5	15.8	19.8	29.4	30.6
	Tmin (^{0}C)	17.0	8.5	3.8	3.5	3.7	5.4	10.3	14.5	24.2
	Precipitation (mm)	30.6	63.9	63.2	10.6	35.8	148.1	56.2	25.0	14.9
	Rad. (MJm^{-2}day^{-1})	9.1	6.7	4.9	6.9	8.1	8.7	9.4	15.4	17.4
	Evap. (mm day^{-1})	3.2	1.8	0.9	2.0	1.4	3.0	2.0	4.8	5.8

Tmax: Mean maximum temperature; Tmin: Mean minimum temperature; Rad: Radiation; Evap.: Evaporation.

Table 4. Mean for some characteristics of open pollinated and hybrid cultivars in 12 experiments

Cultivars	Days to SF	Days to physiological maturity	Duration of SFP (day)	Mean temperature during SFP (^{o}C)	Seed weight (mg)	Seed yield (kg ha^{-1})
OP	127	173	46	17.3	3.8	3035
Hybrid	114	164	50	16.8	4.2	3332

OP: Open pollinate, SF: Seed filling, SFP: Seed filling period.

The duration of SFP in OP and hybrid cultivars responded linearly to the temperatures experienced during this period, and its duration increased at lower temperatures (Fig. 2). In both groups of cultivars, there was a negative linear relationship between mean air temperature during SFP and the duration of the period which explained 78% and 81% of the variation of SFP in OP and hybrid cultivars, respectively (Fig. 2). For each degree increase in mean air temperature during SFP, the duration of SFP shortened by 2.36 and 2.16 days in OP and hybrid cultivars (Fig. 2). Seed filling period commenced earlier in hybrids (114 days) as compared to OP (127 days) cultivars (Table 4). Consequently, SFP was longer in hybrids and experienced cooler temperatures which led to heavier SW and higher SY (Table 4). Lower temperatures extended the duration of SFP in both OP and hybrid cultivars (Fig. 2).

The mean air temperature during SFP, duration of SFP, SW and SY of OP and hybrid cultivars were 17.3 and 16.8 °C; 46 and 50 days; 3.8 and 4.2 mg; and 3035 and 3332 kg ha^{-1}, respectively (Table 4).

The ability of the crop to produce assimilates for developing seeds was an effective determinant factor for SW. There was a linear relationship between LAI at the onset of SFP and SW, explaining 72% and 74% of the variation in SW of RGS003 (OP) and Hyola401 (hybrid) cultivars, respectively (Fig. 3). For each unit increase in LAI at the onset of SFP, SW of RGS003 and Hyola401 cultivars increased by 0.431 and 0.549 mg, respectively (Fig. 3).

In addition, there was a linear positive relationship between ADM at the onset of SFP and SW, explaining 76% of the variation in SW for RGS003 and Hyola401 cultivars (Fig. 4). For each gm^{-2} increase in ADM at the onset of SFP, SW of RGS003 and Hyola401 cultivars increased by 0.0019 and 0.0024 mg, respectively (Fig. 4), indicating a greater response of Hyola401 (hybrid) to increased LAI and ADM at the onset of SFP when compared to RGS003 (OP). No significant relationship was found between SW and SN m^{-2}, indicated that SW of oilseed rape was not affected by SN m^{-2}, i.e. SW of oilseed rape cultivars was not sink limited.

There was a linear positive relationship between PTQ during SFP and SW, explaining 72% and 70% of the variation in SW for OP and hybrid cultivars, respectively (Fig. 5). For each unit increase in PTQ during SFP, SW of OP and hybrid cultivars increased by 6.63 and 7.93 mg, respectively (Fig. 5).

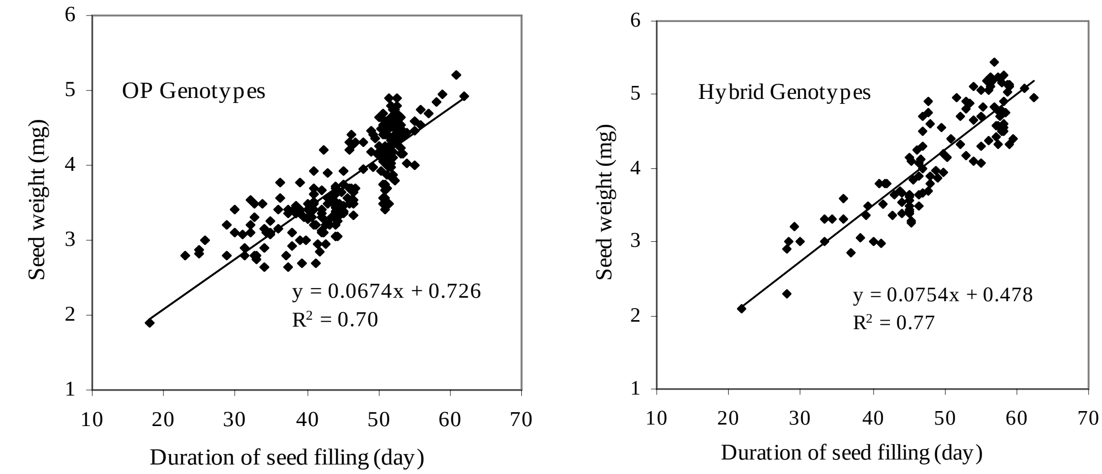

Fig. 1. Relationship between duration of seed filling period and seed weight in open pollinated (OP) and hybrid oilseed rape cultivars.

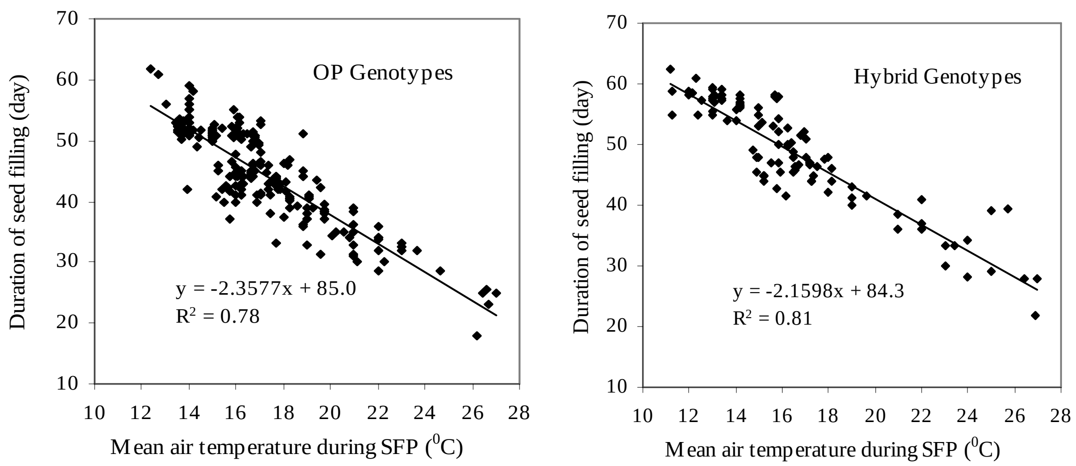

Fig. 2. Relationship between mean air temperature during seed filling period (SFP) and duration of SFP in open pollinated (OP) and hybrid oilseed rape cultivars.

Therefore, in both group of cultivars, the variation in SW could be explained by cumulative light absorption during the critical period of SF, therefore; temperature and radiation interactions during the period, as showed by PTQ. The relationships between PTQ during SFP and SW showed a greater response of hybrid cultivars to increase in PTQ during SFP as compared with OP cultivars.

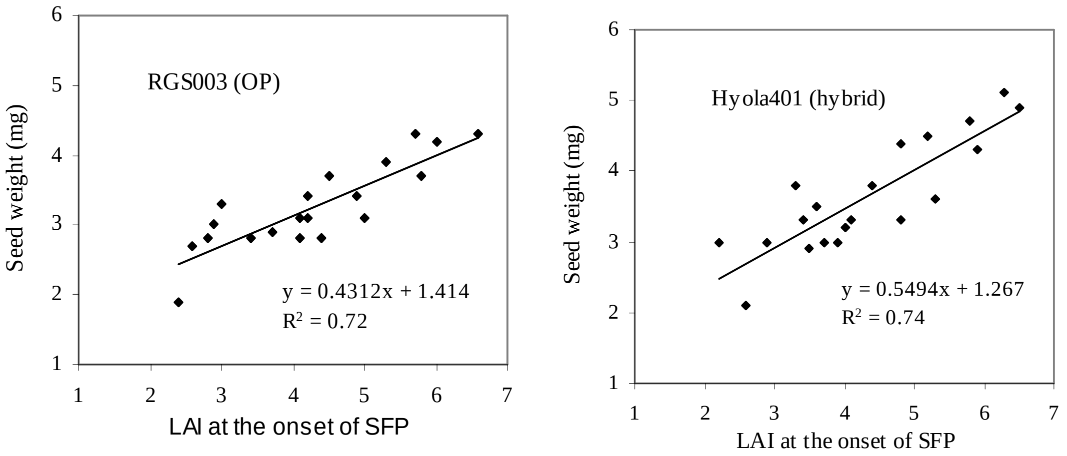

Fig. 3. Relationship between leaf area index (LAI) at the onset of seed filling period (SFP) and seed weight in RGS003 (OP= open pollinated) and Hyola401 (hybrid) oilseed rape cultivars.

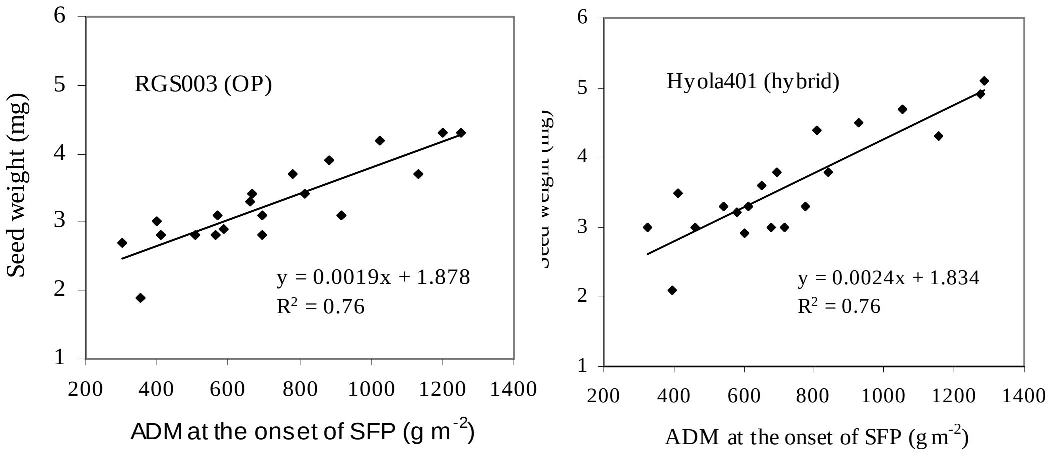

Fig. 4. Relationship between above ground dry matter (ADM) at the onset of seed filling period (SFP) and seed weight in RGS003 (open pollinated) and Hyola401 (hybrid) oilseed rape cultivars.

Discussions

Seed weight in oilseed rape depends on three main sources: current assimilates produced by photosynthesis in green leaves and stems, remobilization of the stem reserved carbohydrates to the developing seeds, and assimilates produced by the pods (Habekotte, 1993; Johnson *et al.*, 1995; Plaut *et al.*, 2004). The relative contribution of remobilized assimilates from these sources to seeds is dependent on environmental conditions, the magnitude of biotic and abiotic stresses and to some extent cultivar (Plaut *et al.*, 2004).

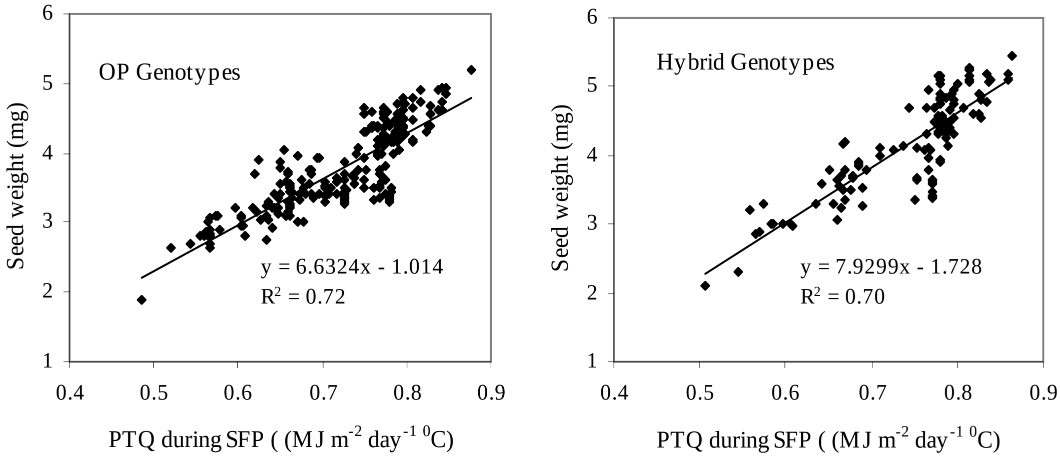

Fig. 5. Relationship between photo-thermal quotient (PTQ) during seed filling period (SFP) and seed weight in open pollinated (OP) and hybrid oilseed rape cultivars.

In these experiments, hybrid cultivars displayed higher ADM at the onset of SFP, longer SFP, heavier SW, and higher SY, suggesting the importance of assimilate supply at the onset of SFP and duration of SFP in SW determination.

Angadi *et al.* (2000) also showed the importance of air temperature during SFP in determining the duration of SFP, and therefore, SW. This is in accordance with findings of present study (Fig. 1 and 2). In both OP and hybrid cultivars, mild temperatures increased the rate of plant development, reduced the duration of the SFP the SW (Fig. 1 and Fig. 2). However, the direct effects of temperatures on SW depend on the Cultivar and its adaptability. In these experiments, the number of days from emergence to onset of SF in hybrid cultivars was considerably less than OP cultivars (Table 4). On the other hand, SFP commenced earlier in hybrid Cultivar and experienced cooler temperatures during the SFP (Table 4), which appeared to be responsible for longer SFP, provided accumulation of more assimilates in developing seeds and led to in heavier seeds. This might be due to increased photosynthesis as SFP occurred under cooler temperatures and higher PTQs, and is in accordance with previous reports in oilseed rape (Habekotte, 1997; Adamsen and Coffelt, 2005). The positive effect of longer SFP on SW (Fig. 1 and 2) has also been reported in other species such as durum wheat (Garcia del Moral *et al.,* 2003) and triticle (Royo *et al.,* 2000).

The combination of years and sowing dates provided wide variation in environmental conditions during SFP. As duration of SFP in oilseed rape is a function of temperature during this period (Habekotte, 1997), higher temperatures shortened its duration (Fig. 2). High temperatures, accelerated the rate of plant development, shortened the duration of SFP (Fig. 2), and reduced the SW (Fig. 1). It is also observed in other species (Entz and Flower, 1991; Chimenti and Hall, 2001). Reports from other researchers confirmed that cooler growing conditions during SFP improved oilseed rape SW and SY (Kirkland and Johnson, 2000; Aguirrezabal, *et al.*, 2003). Results of the present study showed that increase in SW was due to increase in SFP, LAI and ADM at the onset of SFP, and PTQ during SFP. This implies that optimum weather conditions such as high radiation and mild temperatures as well as supply of assimilates at the commencement of SFP were important factors determining SW in oilseed rape.

The non-significant relationship between SN m^{-2} and SW showed that SN per unit area was not a limiting factor for seed development. There was similar variability in both OP and hybrid cultivars in SW response to SN m^{-2}. In wheat, Acreche and Slafer (2006) found that when the number of grains m^{-2} increased, a concomitant increase in the proportional contribution of grains that are smaller took place and led to a non-significant relationship between the number of grains m^{-2} and SW. Miralles and Slafer (1995) indicated that the reduction in the average grain weight by increases in SN m^{-2} was not attributed to an increased competition for assimilates.

LAI and ADM at the onset of SFP were both significantly correlated to SW (Fig. 3 and Fig. 4), indicated that a large leaf area resulted in increased ADM and SW. In addition to the effects of the high LAI and ADM at the onset of SFP, and the mild temperatures during SFP (Table 4), the higher SW of hybrid cultivars, compared with OP cultivars, may have been due to better utilization of absorbed radiation for SW (Habekotte, 1997) or stronger response of SW to available assimilates in hybrid cultivars. However, a high value of LAI at the onset of SFP is a prerequisite to attain sufficient light absorption during the critical period of SF (Habekotte, 1997).

The strong relationship of SW with ADM at the onset of SFP indicated that

SW was driven by the produced cumulative carbohydrates before SF stage, and probably the ability of the crop to remobilize reserved carbohydrates to developing seeds. Habekotte (1993) found that oilseed rape pod density and SW were linearly related to cumulative dry matter production of the crop until the end of flowering, i.e. total assimilate availability over SFP. In maize, Borras and Otegui (2001) indicated that final grain weight was a product of the sink capacity of individual grain and the availability of assimilates to fill these sinks. In oilseed rape, Chongo and McVetty (2001) did not find any correlations between SY and leaf photosynthetic rates. However, the high-yielding group cultivars displayed the highest net photosynthetic rates, utilized water more efficiently at early flowering, and produced the highest total dry matter and SY. They concluded that the green leaf area during the early reproductive stage in oilseed rape is important factor in determination of SY.

The stability of these relationships over a wide range of years and experiments supports the conclusion that LAI and ADM at the onset of SFP are important determinants of oilseed rape SW. However, ADM is the product of crop growth rate and growth duration, both indicated the potential for improvement in SW by manipulating crop phenology. Higher LAI increased the interception of solar radiation, and thus a greater CO_2 fixing ability by the crop, led to accumulation of more assimilates. In some other species the SFP assimilate availability conditioned SW (Borras *et al.*, 2003; Ruiz and Maddonni, 2006). These results suggest that SW primarily depends on the resource availability which agrees with the findings of other researchers in some other species such as sunflower (Aguirrezabal, *et al.*, 2003).

Conclusion

In this study, a great proportion of the variation observed in SW was related to environmental conditions during the critical period of SF. It is postulated that potential SW is determined before the commencement of SFP; hence, increases in LAI and ADM at the onset of SFP increased final SW. The established relationships in this study explained that great proportion of the variability in SW for both groups of cultivars. These relationships are simple tools that could be applied in simulation models for SW in oilseed rape under a wide range of environmental conditions. The relationships of SW with LAI and ADM at the onset of SFP, temperature and PTQ during SFP over years, environmental conditions, sowing dates and cultivars showed that these variables are determinants of oilseed rape SW. Hence, further increase in yield through increased SW could be obtained through improvement in one or a combination of these factors.

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