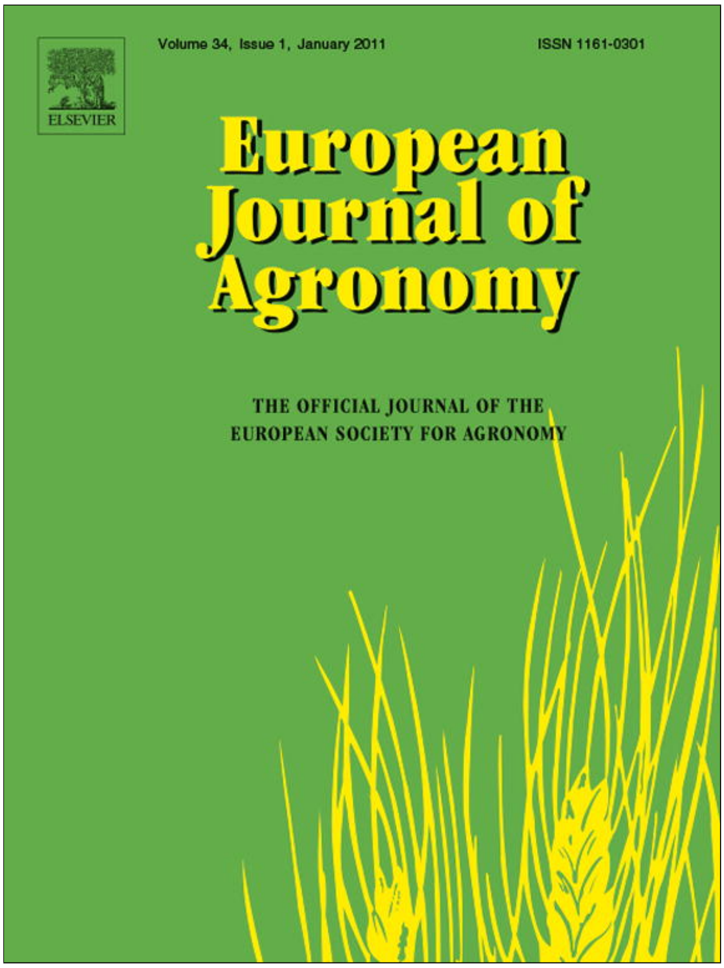

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Global trends of rapeseed grain yield stability and rapeseed-to-wheat yield ratio in the last four decades

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ABSTRACT

Increases in crop yields are important to ensure food supply for humanity. Global yield trends have been analyzed considering public national average data, mainly for cereals but not for rapeseed. As rapeseed and wheat compete for land in crop rotation, it is also important to know how the rapeseed-to-wheat yield ratio is modified in different environments so as to make rapeseed an attractive alternative for farmers around the world. The present study analyzed historical records of rapeseed from FAO determining yield stability trends over the last 40 yr, as well as rapeseed competitiveness compared to wheat. Twelve countries representing a wide range of environments and farming systems were taken into account. Regressions were fitted to the rapeseed yield/time relationships and residuals of these regressions were used to evaluate trends in yield stability. Results showed a global rapeseed yield gain of 27 kg ha^{-1} yr^{-1} along the past 40 yr, although fluctuating among decades. In relative terms to 1970, world rapeseed yield increased 3.4% yr^{-1}. Yield gain in different countries varied from 15 to 40 kg ha^{-1} yr^{-1}, exhibiting linear, bi- or tri-linear yield trends. Opposite yield trends were observed for Chile and the UK, with sustained yield gain for the former and leveling off for the latter since the mid 1980s. This does not seem to be related to the supply of environmental resources (both countries yielding >3000 kg ha^{-1}). A high variability was detected in national yields (0–750 kg ha^{-1} or 0–60% of yield) and yield stability did not increase over the last 40 yr in any country. Rapeseed and wheat yields, expressed in relative terms to their values for 1970, increased in a similar proportion over the last four decades. Global rapeseed-to-wheat ratio ranged 40–60% over the last 40 yr, but rapeseed yields can increase up to 80–100% with respect to wheat in poor environments for wheat (<2000 kg ha^{-1}), leveling off around 40% in high wheat yields environments (>4000 kg ha^{-1}). It was concluded that rapeseed yields have increased steadily in the last 40 yr in most studied countries, the yield gain was not accompanied by greater yield stability, and rapeseed competitiveness compared to wheat is at least 40–50% in environments with good supply of resources.

1. Introduction

At world level, rapeseed oil from *Brassicas* species with low erucic and low glucosinolates is the third most consumed oil after soybean and palm oil, and the third most consumed meal (crushed seed) after soybean and cotton. In recent years, the demand for rapeseed and other oilseed crops has increased as a result of the global energy crisis and the rising demand for biofuels (Oil Word, 2010). Rapeseed has a long tradition into the cropping systems in many European countries as well as in Asia, with China, Canada, India, Germany and France as the major producing countries throughout history (Gupta and Pratap, 2007; Casséus, 2009; Bhattacharjee, 1991; Singh and Sharma, 2007; Brauer and Röbbelen, 1989; Anon, 1981). Other countries from Oceania and America, such as Australia, the USA, Chile, Brazil, and Argentina, have a shorter-standing tradition in oilseed production at a large commercial scale (Salisbury and Wratten, 1999; Raymer et al., 1990; Lizama Arias, 1990; Tomm, 2007; Iriarte and Valetti, 2008).

Global yield trends in cereal crops have been analyzed by several studies aimed at assessing rates of genetic gain and changes in potential and achievable yields (Evans, 1993; Tollenaar and Lee,

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2002; Fischer et al., 2009; Fischer and Edmeades, 2010). Nevertheless, yield trends can differ among specific countries, representing similarities or masked differences between countries with respect to global trends (Calderini and Slafer, 1998). When public data are analyzed (e.g. FAO) and several countries are considered in terms of their national average yield, important variations in grain yield appear, due to different genetic improvement, environmental resources, and/or technological level and crop management. In the case of rapeseed, recent studies have shown that yields on farms have not increased since the mid 1980s in countries such as the UK (Berry and Spink, 2006) and Finland (Peltonen-Sainio et al., 2007), concluding that crop management factors instead of lack of genetic improvement, have caused yield stagnation in both countries. However, as far as we know, there are no studies that have globally analyzed changes in rapeseed yield over a long time period, considering a broad group of countries from different production areas around the world. The first hypothesis tested was that rapeseed yields increased during the last 40 yr but the magnitude differed among countries.

Similar to many other grain crops, increasing rapeseed yield is one of the most important objectives for breeders and farmers, and enhancing yield stability is also important for cropping systems and widespread adoption by farmers. Analyzed using the traditional Finlay and Wilkinson (1963) approach, a genotype can be studied by the relationship between yield and environmental indices (*i.e.* average yields of all genotypes in each particular environment when evaluated in a wide range of environmental conditions). The slope of the lineal regression between yields (for that genotype) and of the environmental indices represents the genotype responsiveness, while the deviation with respect to the fitted lineal model (residuals) provides a measure of yield stability (*i.e.*, to lower residuals, more stable yields around the value predicted by the model). In the case of barley and wheat, the most productive genotypes normally register poor stability (Perry and D'Antuono, 1989; Slafer and Andrade, 1993; Calderini and Slafer, 1999; García del Moral et al., 2003; Arisnabarreta and Miralles, 2006), although some exceptions with high grain yield and yield stability can be found in maize (Tollenaar and Lee, 2002). A similar approach can be applied to national average data of crop yields, and this methodology of analysis has demonstrated that yield stability in the case of wheat has not changed for a wide range of countries analyzed in different studies during the last century (Slafer and Kernich, 1996; Calderini and Slafer, 1998). It is expected that as yield potential improve and the agronomic management practices are also better in the present, the current yield stability of rapeseed could be higher than in the past. However, there is no evidence in the literature of how yield stability has been modified in rapeseed during the last decades considering world production and individual countries. Therefore, the second hypothesis tested was that the rapeseed yield increase throughout the last four decades was followed by greater yield stability.

At the same time, the size of the harvest areas could also modify the stability of the crop over the time. The rapeseed growing areas differ among countries, so rapeseed growing areas that cover a wide territory could exhibit lower yield variability over the time, reducing production risks in the country as a whole, respect to those countries with a reduced rapeseed area production. Thus, the third hypothesis is that the higher the harvest area the lower the rapeseed yield stability.

Rapeseed is one of the few winter oilseed crops which compete economically with winter cereal crops such as wheat and barley. Thus, the yield of rapeseed has to be competitive against other winter cereals in the farming schemes, so as to be an attractive alternative for farmers (Diepenbrock, 2000; Beddington, 2010). In order to adequately compare both crops, the greater energy cost to produce high-oil grains should be considered. The high oil content in rapeseed grains (typically 30–50% throughout years) limits its yields compared to wheat yields. Unfortunately, the FAOSTAT database does not provide national grain oil contents that would enable the adjustment of wheat and rapeseed yields by their energy cost. To overcome this difficulty, and as rapeseed is mainly grown in the same production environments (areas and seasons) as wheat, comparing rapeseed yields in terms of wheat would be useful to evaluate the rapeseed performance through the environmental index estimated through wheat yields. A previous report on particular environments of Australia indicated that rapeseed yields can be placed at about 40–60% of wheat yield (Holland et al., 1999), but the validity of this relationship for a broader group of countries and different levels of wheat yield (as an indicator of different potential environments) has not been verified. Could be speculated that even when the oil content vary among the environments, the lower proportion of rapeseed yield, respect to wheat, could be similar (about 50%) but depending on the variations in the quality of the environments that determine changes in oil grain content in rapeseed that yield proportion, respect to wheat, could be modified. Thus, the fourth hypothesis tested was that rapeseed yield is at least 40% of wheat yields in a broad range of countries with differing environmental indexes estimated through wheat yields.

The main objectives of the present study were to analyse: (i) rapeseed yield and yield stability trends, and (ii) rapeseed competitiveness compared with wheat, in a wide range of countries from different continents, representing contrasting environmental conditions throughout the world, based on the historical records (last 40 yr) from the FAO database (FAOSTAT, 2011).

2. Materials and methods

2.1. Data selection

The information was obtained from FAOSTAT (2011), choosing the rapeseed crop item (including Swede and turnip rape, but not mustard seed). The FAOSTAT database does not discriminate between winter and spring crops of rapeseed and wheat in each country. Although data precision from FAOSTAT could be affected by the consistency among countries of the yield-estimating methods, crop failure estimations and methodological changes over time, FAOSTAT is the only available public free-access data source that could be used for this kind of analysis (Calderini and Slafer, 1999; Berry and Spink, 2006; Fischer and Edmeades, 2010).

Twelve countries (Argentina, Australia, Brazil, Canada, Chile, China, France, Germany, India, Poland, the United Kingdom, and the USA) were included in the present study, thus covering the Americas, Asia, Europe and Oceania. Data containing the whole world were also included. The criteria used to select the countries were: (i) average rapeseed production during the last 10 yr (2000–2009) ranked in descending order, and (ii) fundamental differences regarding geographic site, to represent all continents with a wide range of climatic conditions and yield levels. Countries which have changed names along years (e.g. ex-USSR and the emergent republics in that region since 1993) were excluded because it was not possible to pool data from the last decades. Ten of the 12 countries have records of rapeseed production prior to 1970, but Brazil and the USA only have records from 1980 and 1987, respectively. For the selected 12 countries and the whole world, wheat yield data (1970–2009) were also obtained from the FAOSTAT database and used for comparison with rapeseed yield.

2.2. Analyses

To characterize the yield trend throughout the years in each country, average yields were regressed against years using linear ($y = a + bx$), bi-linear ($y = a + bx$ if $x \le c$ and $y = a + bc + d(x - c)$ if

$x > c$) or tri-linear ($y = a + bx$ if $x \leq c$; $y = a + bc + d(x - c)$ if $e \leq x > c$ and $y = a + bc + d(e - c) + f(x - e)$ if $x > e$) regressions, depending on the best fit for the data set in each particular case: y standing for yield, a the intercept, b the rate of yield gain during the first period, c the year when the first cutoff point occurred, d the rate of yield gain during the second period, e the year when the second cutoff point occurred, and x the year. The model finally accepted for each case was the one exhibiting both a high coefficient of determination and the lowest random distribution of residuals throughout the years. Significant differences in slopes among periods or countries were assessed by confidence comparison intervals ($P < 0.05$). To assess changes in yield stability throughout the years, the residuals of each regression analysis were used. Negative values of relative yield residuals were multiplied by −1. Yield variability was assessed as the difference between actual and predicted data, hereafter referred to as 'yield residuals', according to Slafer and Kernich (1996). Furthermore, as both average yields and yield gains were different among countries, 'relative yield residuals' (*i.e.*, the difference between actual and predicted data was presented as percentage of predicted data) were used for assessing trends in yield stability in relative terms as stated in Calderini and Slafer (1998). Relationships between yield residuals and harvested area and rapeseed yield level were also assessed for the last 10 yr (when high-yielding genotypes are expected to be present in all countries). Variations on the ratio of rapeseed to wheat yields were analyzed by linear regression against wheat yield for the selected countries, and contrasted with global trends in order to find a rule of thumb to readily assess rapeseed yield prospects and check the stability of the ratio among environments. Relative rapeseed yield (with respect to wheat) was calculated as the ratio between rapeseed yield and wheat yield multiplied by 100. Wheat yield level was used in the axis x as an indicator of environmental index including both, potential environment and crop management (Holland et al., 1999). Due to the spurious correlation generated by placing wheat yield in both x and y axes, only the dispersion of the relationship was analyzed, but not its parameters (Brett, 2004).

3. Results

3.1. Global trends in harvested area and rapeseed yield

The global world average yield was doubled from 1970 to 2009, increasing from *ca.* 800 to 1900 kg ha^{-1}, with an increase rate of *ca.* 27 kg ha^{-1} yr^{-1} for the whole period (Fig. 1). For the same period, the harvested area steadily increased, reaching 31 million ha in 2009, with an increase rate of 600,000 ha yr^{-1} (Fig. 1), which represents a three-fold rise.

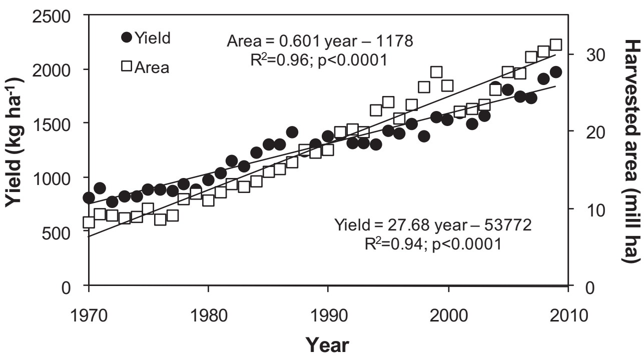

Fig. 1. Global world average yield (kg ha^{-1}) and harvested area (million ha) of rapeseed for the period 1970–2009. Lines correspond to the adjusted linear regressions with the corresponding equations, correlation coefficients and probabilities.

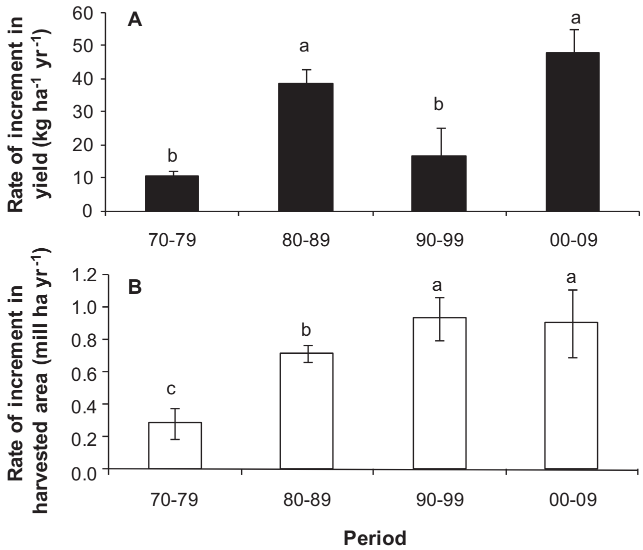

Fig. 2. Rates of increment in (A) yield (kg ha^{-1} yr^{-1}) and (B) harvested area (million ha yr^{-1}) of global rapeseed for different decades during the 1970–2009 period. Different letters over the bars indicate significant differences ($P < 0.05$) among periods. Vertical bars indicate the standard errors.

Yield and harvested area increases were significantly different ($P < 0.05$) depending on the period under consideration. From 1970 to 1979, the yield gain was 10.8 kg ha^{-1} yr^{-1}, increasing during the eighties at *ca.* 39 kg ha^{-1} yr^{-1}, although it fell to half that amount in the nineties (16.7 kg ha^{-1} yr^{-1}). However, from 2000 to 2009, the rate increased again up to 48 kg ha^{-1} yr^{-1} exhibiting the highest yield gains in the whole period considered (Fig. 2). Harvested area showed a low increment in the seventies, followed by increasing rates (0.9 million ha yr^{-1}) during the eighties and nineties (Fig. 2).

3.2. Rapeseed yield and yield stability in selected countries around the world

The production of the 12 selected countries included in this analysis represented 88% of the total rapeseed production around the world for the last 10 yr, with five countries concentrating 76% of the total production: *i.e.* China, Canada, India, Germany and France (Table 1). Regarding yield performance from 1999 to 2009, four countries (Germany, Chile, France and the UK) reached the highest national average yields, *i.e.* >3000 kg ha^{-1}. Poland produced 2500 kg ha^{-1} while the rest of the selected countries exhibited medium to low national yields ranging from 1000 to 1700 kg ha^{-1} (Table 1).

For the whole 1970–2009 period, selected countries showed different yield trends throughout the years (Fig. 3). Most countries exhibited linear rate increases in yield at rates that were from 15 to 40 kg ha^{-1} yr^{-1}, but the highest yield gains per year were observed in countries where the relationship between yield and year was fitted by bi- or tri-linear models, such as Chile, Brazil and the UK (Fig. 3; Table 2). The highest yield gain, 98 kg ha^{-1} yr^{-1}, was observed in Chile from 1985 to the present, followed by the UK with 96 kg ha^{-1} yr^{-1} during the 1970–1984 period, and Brazil with 93 kg ha^{-1} yr^{-1} between 1992 and 2002. The USA has not shown significant yield increase since the 1980s, when production began. No significant yield gains were observed in the UK and Brazil from 1984 and 2000, respectively, while in Chile the yield gains previous to 1985 were close to zero (Fig. 3).

The variations of rapeseed production for the different countries analyzed in the present study were associated to both harvested area and yield (Table 3). However, in many countries rapeseed production was better when correlated with variations

Table 1
Absolute and relative production, harvested area (ha) and average grain yield (kg ha^{-1}) of rapeseed and national wheat yield for the 2000–2009 period in the world and in the different countries selected for this study.

	Rapeseed				Wheat
Country	Production (ton)	Production (%)	Harvested area (ha)	Yield (kg ha^{-1})	Yield (kg ha^{-1})
China	11,821,618	25.6	7,272,013	1720	4248
Canada	8,374,070	18.1	6,104,500	1603	2443
India	6,142,570	13.3	6,300,000	1032	2721
Germany	4,767,510	10.3	1,471,200	3591	7426
France	4,070,562	8.8	1,480,810	3207	6954
United Kingdom	1,698,573	3.7	581,000	3124	7808
Australia	1,424,632	3.1	1,394,000	1150	1567
Poland	1,523,423	3.3	809,970	2543	3768
United States of America	715,483	1.6	329,780	1573	2789
Brazil	88,600	0.19	60,000	1700	1987
Chile	43,384	0.09	25,135	3366	4359
Argentina	18,245	0.04	39,256	1456	2366
World	46,206,452	100	31,120,565	1720	2840

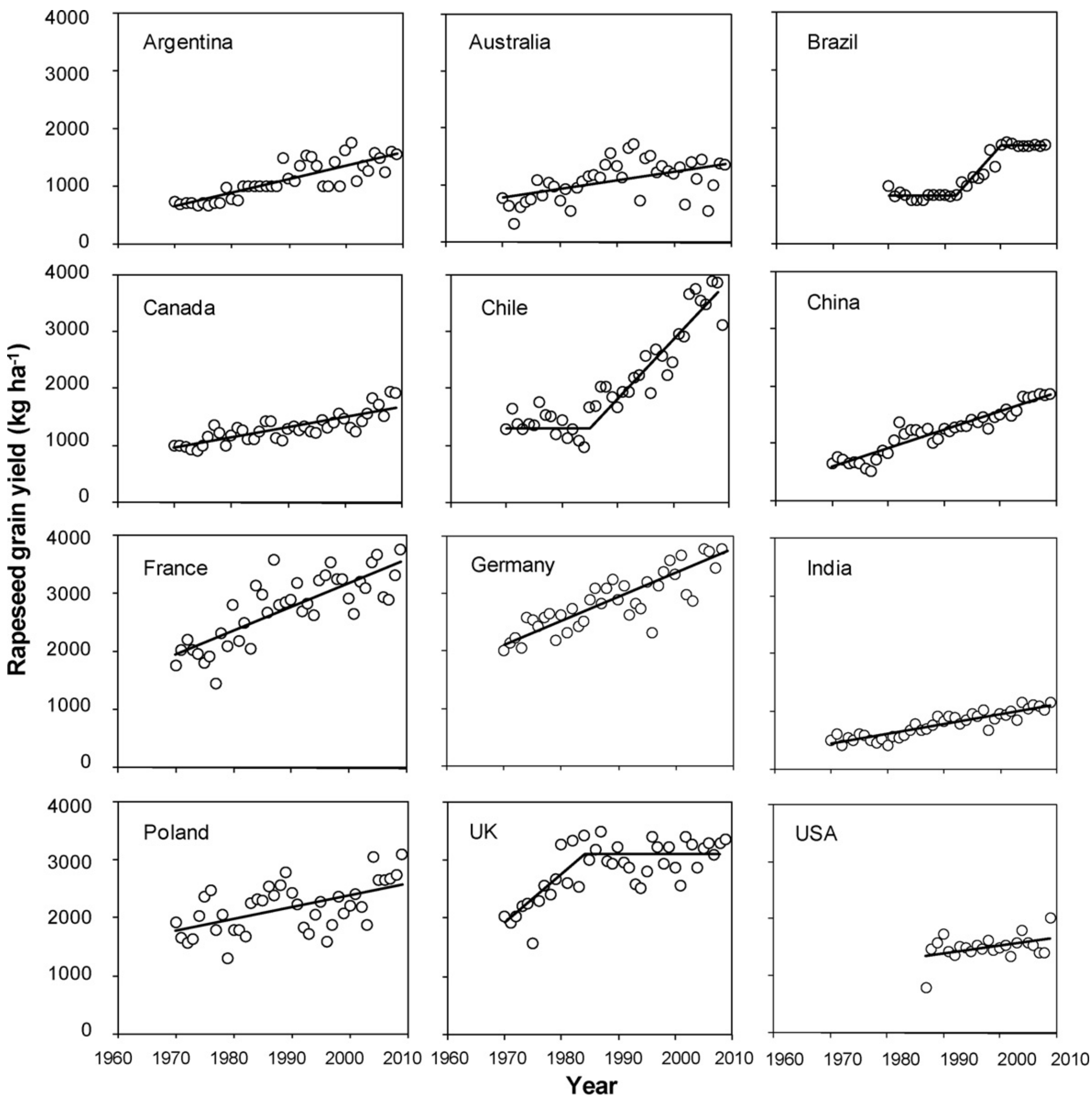

Fig. 3. National average rapeseed yield (kg ha^{-1}) in 12 countries for the 1970–2009 period. Solid lines were fitted by bi-linear (Chile and the UK), tri-linear (Brazil) and linear (rest of countries) models (see models parameters in Table 2).

Table 2
Outputs [coefficient of determination (R^2), breakpoint indicating the year when a change in the slope occurred and maximum slopes] of regression models fitted to yield/years relationships for the period 1970–2009 in 12 selected rapeseed producing countries (ordered alphabetically). Standard errors are shown between brackets.

Country	Model	R^2	Breakpoints	Maximum slope (kg ha^{-1} yr^{-1})
Argentina	Linear	0.68		23.0 (2.6)***
Australia	Linear	0.25		15.0 (4.3)***
Brazil	Tri-linear	0.83	1992 (1.4) 2000 (2.0)	92.7 (17.7)**
Canada	Linear	0.66		15.8 (2.0)***
Chile	Bi-linear	0.83	1985 (2.0)	98.5 (4.7)***
China	Linear	0.89		31.8 (1.9)***
France	Linear	0.63		40.0 (5.1)***
Germany	Linear	0.71		39.4 (4.1)***
India	Linear	0.82		17.4 (1.3)***
Poland	Linear	0.26		18.0 (5.0)**
United Kingdom	Bi-linear	0.43	1984 (2.3)	95.9 (5.2)***
United States of America	Linear	0.08		8.3 (6.2) NS

Significant level: NS ($P \geq 0.05$), ** ($P < 0.01$), *** ($P < 0.001$).

in harvested area rather than with variations in yield. Moreover, in some countries, as Chile and the USA, variations in production were not significant when associated with yield (Table 3).

Yield residuals did not show a clear trend and thereby did not evidence a decrease throughout the time for any country (Fig. 4). India, Brazil, Canada, and China exhibited low residuals (<250 kg ha^{-1}) whereas Australia, Chile, France, Germany, Poland, and the UK showed highest values (>500 kg ha^{-1}).

When residual yield data were expressed in relative terms (%) with respect to predicted yield values using the linear, bi- or tri-linear models (Fig. 5), a high dispersion was observed for all countries with no clear trend along time, similarly to what was observed in the analysis of absolute values. Australia exhibited the highest variability (relative yield residuals ranged 0–60%) throughout all decades, whereas Brazil and the UK exhibited the lowest ones (values <25%). Chile, China, India and the USA showed some kind of variability reduction of relative residual yields along decades, from average residual values of 15% in the seventies to 5–7% in the last 10 yr.

Rapeseed yield variability during the last 10 yr was not clearly associated with rapeseed yield level or harvested area (Fig. 6), although those countries with the largest harvested area such as China, India and Canada exhibited substantially less yield variability compared to the rest of countries (Fig. 6A).

3.3. Rapeseed yield relative to wheat yield

Global rapeseed yield plotted against global wheat yield for the period considered (1970–2009) exhibited a linear relationship with a slope lower than 1, indicating that wheat yield increased at a higher rate than rapeseed yield (Fig. 7A). Nevertheless, when both yields were expressed relative to their values for 1970, the slope was close to 1 (Fig. 7B) indicating that global rapeseed and wheat yields increased in a similar proportion over the last four decades. However, when yields in both species were calculated relative to their values in 1970 for different countries, the slopes were different depending on the particular country. Thus, the slopes ranged from 0.5–0.6 (Brazil, the UK, China) to 1.16 (Australia) (Table 4).

When global world data were analyzed, plotting the relative rapeseed yields (calculated with respect to wheat) against wheat yield, relative rapeseed yield ranged between 50 and 60% of wheat yields for a broad range (1500–3000 kg ha^{-1}) of global wheat yields considering the 1970–2009 period. For particular countries, this relationship showed a high variability, especially in the range of low wheat yields (<2000 kg ha^{-1}), with a trend to decrease as wheat yields increased (*i.e.* >4000 kg ha^{-1}) (Fig. 8). The floor of relative rapeseed yield that could be reached with respect to wheat ranged from 35 to 40%, so, in general terms, it is improbable to obtain rapeseed yields lower than 40% of wheat yield, independently of the environmental offer (quantified by the level of wheat yield). However, in poor environments for wheat production (*i.e.* <2000 kg ha^{-1}), rapeseed could reach similar yield values (90–100%) to wheat in 9% of cases (14 of 156 cases, Fig. 8) whereas in 33% of cases, rapeseed reached yields higher than 70% of wheat yields (52 of 156 cases, Fig. 8).

Table 3
Correlation coefficients (r) between rapeseed production (Prod, ton) and harvested area (A, ha) and yield (kg ha^{-1}) in 12 selected countries (ordered alphabetically) and the world for the period 1970–2009.

Country	Prod *vs A*	Prod *vs* yield
Argentina	0.96***	0.57***
Australia	0.96***	0.37*
Brazil	0.99***	0.73***
Canada	0.96***	0.85***
Chile	0.90***	0.14 NS
China	0.96***	0.96***
France	0.98***	0.81***
Germany	0.98***	0.88***
India	0.95***	0.94***
Poland	0.97***	0.87***
United Kingdom	0.99***	0.74***
United States of America	0.99***	0.26 NS
World	0.98***	0.978***

Significant level: NS ($P \geq 0.05$), * ($P < 0.05$) ** ($P < 0.01$), *** ($P < 0.001$)

Table 4
Outputs [coefficient of determination (R^2) and slopes] of linear regression models of rapeseed yield *vs* wheat yield, both in relative values respect to 1970 for the period 1970–2009 in 12 selected rapeseed producing countries (ordered alphabetically). Standard errors are shown between brackets.

Country	R^2	Slope
Argentina	0.46	0.96 (0.17)***
Australia	0.68	1.16 (0.13)***
Brazil[a]	0.39	0.51 (0.12)***
Canada	0.75	1.02 (0.09)***
Chile	0.82	0.91 (0.06)***
China	0.91	0.60 (0.03)***
France	0.75	0.83 (0.07)***
Germany	0.71	0.65 (0.06)***
India	0.84	0.89 (0.06)***
Poland	0.55	0.79 (0.11)***
United Kingdom	0.58	0.56 (0.07)***
United States of America[a]	0.06	0.64 (0.55) NS
World	0.94	1.27 (0.05)***

Significant level: NS ($P \geq 0.05$), * ($P < 0.05$) ** ($P < 0.01$), *** ($P < 0.001$) for slope different than 0.

[a] Values relative to 1980 and 1987, respectively, for Brazil and USA (beginning of rapeseed production)

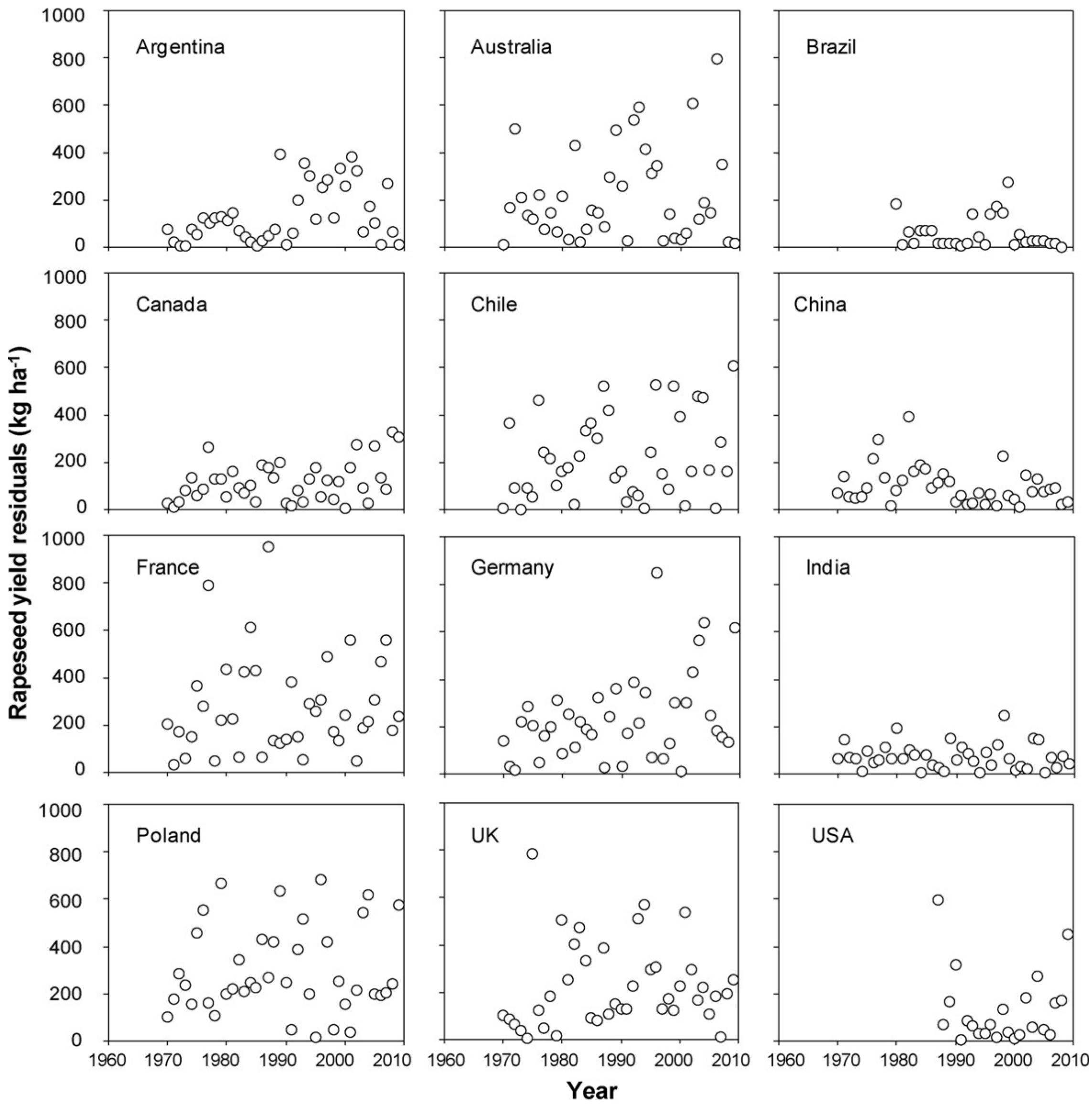

Fig. 4. Yield residuals (kg ha^{-1}) of rapeseed calculated from the regression models used to fit the data in Fig. 3 in 12 countries during the period 1970–2009.

4. Discussion

Along the last four decades, the rapeseed harvested area worldwide increased by 300%, covering 31 million ha. During the same period, global rapeseed yields have increased by 125% from 800 to 1900 kg ha^{-1} with a growth rate of 27 kg ha^{-1} yr^{-1} (Fig. 1), similar to yield gains in other oilseed crops such as soybean (25 kg ha^{-1} yr^{-1}), but lower than that observed for the same period in wheat (39 kg ha^{-1} yr^{-1}) and global cereals (43 kg ha^{-1} yr^{-1} considering rice, wheat and maize; Fischer et al., 2009). In relative terms (referring to 1970), the world rapeseed yield increased 3.4% yr^{-1} whereas wheat and soybean increases were 2.6 and 1.7% yr^{-1} (FAOSTAT, 2011) respectively, indicating that global rapeseed and wheat yields have been increased in a similar proportion in the last four decades (Fig. 7). The analysis also showed that rapeseed yield gains varied greatly among countries from 1 to 2% yr^{-1} (Germany, Australia, Canada, Poland, the UK), 2 to 4% yr^{-1} (India, Argentina, France, Germany) up to 4 and 5% yr^{-1} (Brazil, Chile, China). Although the proportion between winter and spring rapeseed cultivation could varied in some countries (Berry and Spink, 2006; Peltonen-Sainio et al., 2007), it is unlikely that the differences in yield gains can only be explained by changes in the proportion of spring or winter-sown crops as only slight variations in the growth habit was observed in last decades (Berry and Spink, 2006; André Merrien, personal communication).

In the case of wheat and other crops such as rice, maize and potatoes, worldwide production has increased during most of the second part of the 20th century as a result of increased yields derived from the 'green revolution', without significant increases in the harvested area (Slafer et al., 1994; Fischer et al., 2009). However, increases in rapeseed production were in general strongly associated to both harvested area and yield gain. In the near future, a worldwide demand for rapeseed (and other oilseeds) is expected due to growing demand for biofuels, since rapeseed provides high quality oil to produce biodiesel (McDonnell et al., 1999; Rashid and Anwar, 2008). Nonetheless, increasing rapeseed production based on the expansion of the cultivated area does not seem a large-scale sustainable strategy for the coming decades. Consequently, yield increases through breeding and/or better husbandry will be necessary for increasing rapeseed production (Beddington, 2010) as for other crops (Fischer et al., 2009).

Taking into account yield gains as the strategy to be pursued in the future, eight out of the 12 countries analyzed in the present study have shown significant linear yield increases since 1970, with

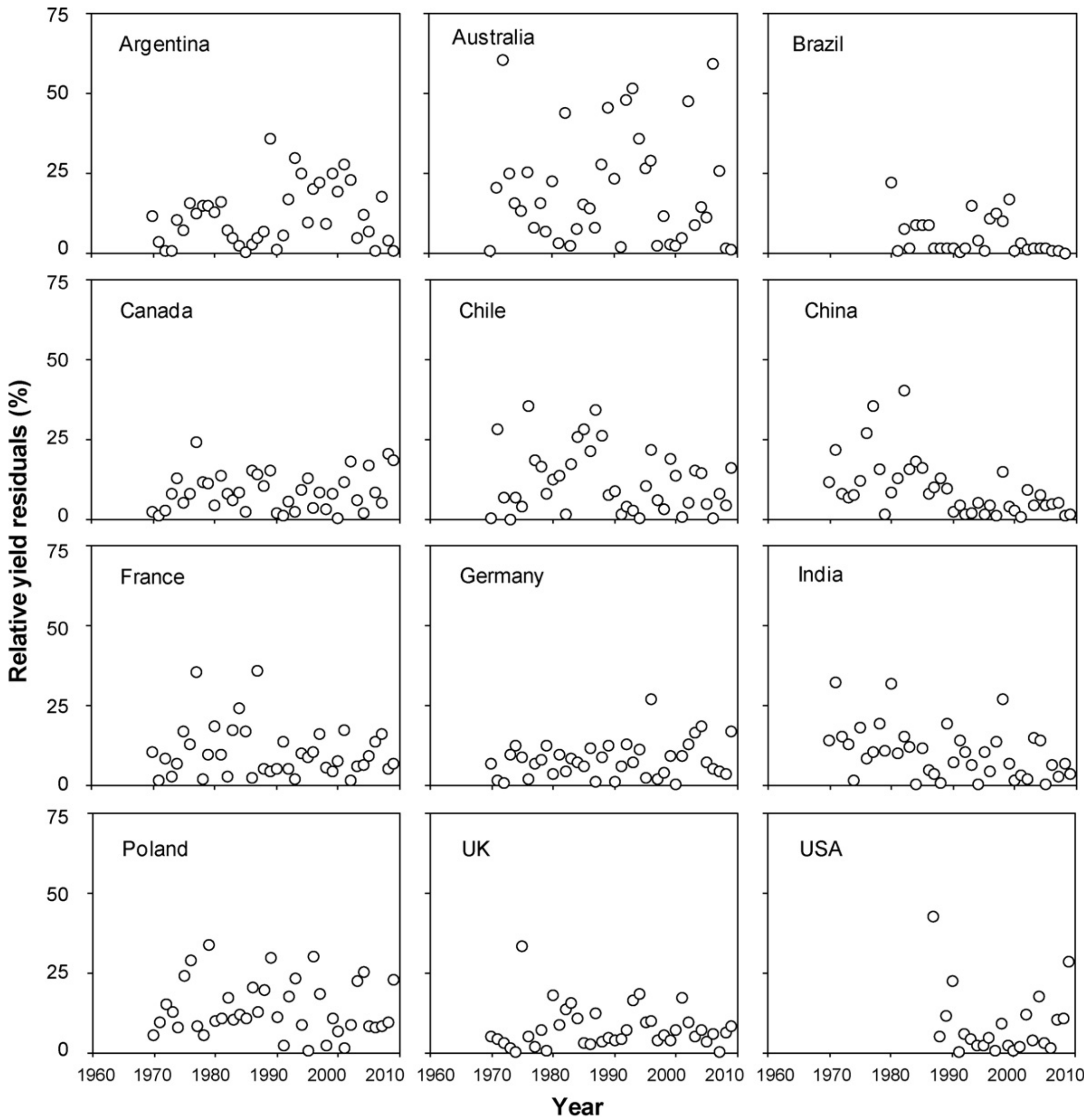

Fig. 5. Relative yield residuals (yield residual/yield predicted ×100) of rapeseed in 12 countries during the 1970–2009 period.

rates ranging from 15 to 40 kg ha^{-1} yr^{-1}. Additionally, the different rates of yield gain among countries do not seem to be clearly related to differences in rapeseed growing tradition. For example, India, Canada, Australia and Poland had similar yield gain rates (15–18 kg ha^{-1} yr^{-1}) in the last forty years, despite their different tradition and history in the cultivation of *Brassicas* at a large commercial scale (Gupta, 2009). The main limitations for yield improvement in these countries could be of a different nature,

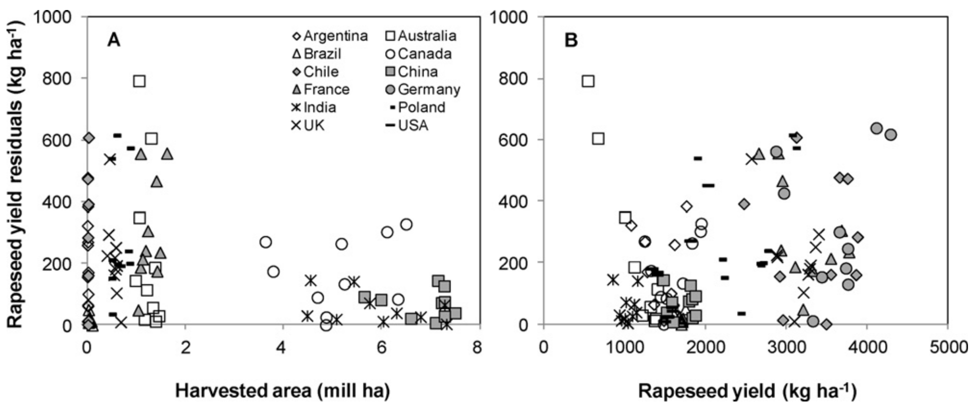

Fig. 6. Relationships between rapeseed yield residuals (kg ha^{-1}) and harvested area (A) or level of rapeseed yield (B) in 12 countries during the 2000–2009 period.

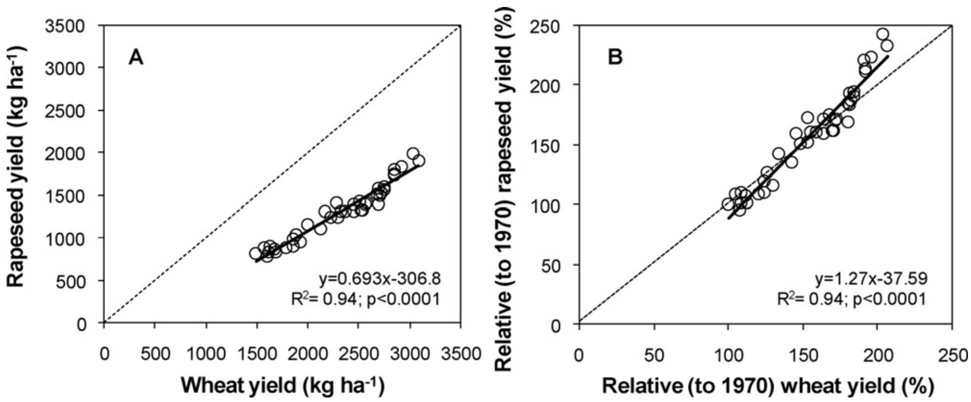

Fig. 7. Relationships between global rapeseed and wheat yields expressed as absolute (A) or relative (B) (respect to yield in 1970) values for the 1970–2009 period. Solid lines correspond to linear regressions and dotted lines to the 1:1 relationship.

ranging from economic reasons, such as price volatility and low modernization of agro-industrial trading system in India (Pahariya and Mukherjee, 2007), to environmental reasons such as frost risk and low amount of water availability for the crop in Australia (Carmody et al., 2003; Robertson and Holland, 2004).

Chile and the UK showed bi-linear patterns with similar breakpoints (1984–1985) and yield gains (95–98 kg ha^{-1} yr^{-1}), but with opposite dynamics throughout the years, as in the past 25 yr the yield has stabilized in the UK while it has been growing steadily in Chile (Fig. 3). In this case, differences between Chile and the UK do not appear to be associated with the environmental offer of resources, as rapeseed is grown in both countries at high latitudes in temperate and wet environments of high yield potential (3000 and 4000 kg ha^{-1} in the last years for the UK and Chile respectively). In fact, in both countries rapeseed is grown under cool temperatures and high irradiance (Sandaña et al., 2009; Spink et al., 2009) resulting in a high photothermal quotient during the crop cycle.

Many other causes may underlie the contrasting behaviour between Chile and the UK in the last decades, as yield advance or levelling off is the consequence of a complex conjunction of agronomic causes (e.g., improved cultivars, mechanisation, timing of sowing, use of fertilizer and pesticides) in addition to socio-economic factors (Evans, 1993) like the production destination. The use of rapeseed as salmon food has greatly increased in Chile, followed by a three-fold increase in Chilean salmon exports during the last 20 yr (Norambuena and González, 2005). The substitution of imported crop commodities, like soybeans, encouraged the association among farmers, fish-feed producers and the salmon industry; canola was subsequently cropped in high yield potential environments of south-central Chile (regions VIII and IX from 36° to 39° latitude S), and since then the canola crop is competitive with other winter crops (Norambuena and González, 2005; Casanueva, 2010). On the other hand, Berry and Spink (2006) have indicated that the main causes of rapeseed yields levelling off in UK farms since the mid 1980s are related to an inadequate combination of crop management factors, such as short rotations, minimal cultivation, less N fertilizer and fungicide application. Similar management causes coupled with the reduced use of pesticides (resulting in yield loss due to diseases) have been associated with rapeseed yield reduction in Finland and other Northern European countries (Peltonen-Sainio et al., 2007). Thus, in the near future, new strategies are necessary for rapeseed in order to overcome the stagnation of yields observed at the farm level in the UK (Berry and Spink, 2006; Beddington, 2010). The same applies for other important grain crops such as wheat (Fischer et al., 2009; Fischer and Edmeades, 2010). Some of the strategies aimed at improving potential yield in rapeseed may include (i) lengthening the duration of the late reproductive phase by increasing the number of grains per unit area, taking advantage of the photoperiodic sensitivity in the vegetative phase (Diepenbrock, 2000; Gomez and Miralles, 2011), (ii) increasing the efficiency of resource capture and use of light, through apetalous flowers, maintenance of active photosynthetic foliar area, and erect clustered pods (Habekotte, 1997a; Sylvester-Bradley et al., 2002), and (iii) raising the harvest index, for example by increasing the number of seeds per pod and pod length (Habekotte, 1997b; Diepenbrock, 2000).

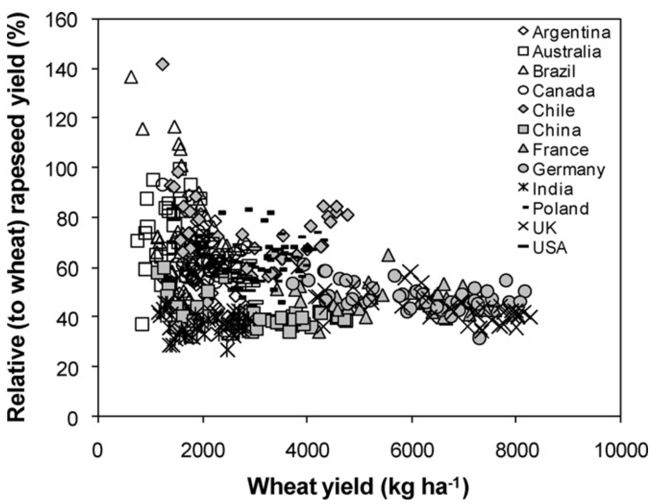

Fig. 8. Relationship between relative (to wheat yield) rapeseed yield and wheat yield in 12 countries during the1970–2009 period.

Several authors agree that the slowing down of on farm yield increases in recent years is not due to a lack of genetic gain, but to inefficiencies in capturing resources and achieving the potential yields, in most cereals (Fischer and Edmeades, 2010) and oilseed crops (Berry and Spink, 2006; de la Vega et al., 2007). Rapeseed breeding since the early 1960s has been shaped by the need to improve the quality of oil and meal, reducing the contents of erucic acid and glucosinolates (Becker et al., 1999). In the past, most rapeseed crops were populations and open-pollinated varieties, but today the main activities in rapeseed breeding worldwide concern the establishment of F1 hybrids cultivars with the objectives of increasing yield potential and obtaining a high-quality rapeseed product (Renard et al., 1997). Despite the undeniable success of breeding rapeseed with 00-quality standard, the first cultivars released were lower in seed and oil yields than the earlier low quality genotypes (Becker et al., 1999). The lagging of the quality genotypes occurs for several reasons, the most important being the drain of selection intensity from yield to quality characteristics

(Velasco and Fernandez-Martinez, 2002; de la Vega et al., 2007). Furthermore, it is worth noting that oil yield (*i.e.*, the product of grain yield and grain-oil concentration) is the main selection criterion of most oilseed breeding programs, but national data only accounts for mean grain yield per unit area (not oil yield), regardless of the relative magnitude of the impact of increases in grain yield and grain-oil concentration on the genetic gains, which may differ depending on the country and the period of time considered (de la Vega et al., 2007). Production goals, such as maximizing oil yield or the gross margin, can be achieved by increasing grain yield per unit area with low-cost management strategies such as the correct selection of genotypes, sowing dates, crop rotations and by reducing harvest losses. Fortunately, the possible trade-off between grain yield and seed oil content is only partial in rapeseed, as was recently demonstrated in a study dealing with lines contrasting in protein content, where the lower energy demand for oil synthesis was not used alternatively to boost protein production, demonstrating that seed and protein yields were higher as the capacity of the line to store oil increased (Peltonen-Sainio et al., 2011). Thus, in agronomic ranges, greater yields promote increases in both oil yield and gross margin.

It is expected that as yield potential is improved and the agronomic management practices (aided by higher technology and use of inputs such as fertilizers and fungicides by farmers) are also better in the present, the current stability of the crops in terms of yield should be higher than in the past. However, this hypothesis is rejected because yield residuals were extremely variable for all countries along years, reaching values as high as 500 kg ha^{-1}, and because no clear trend was observed when residuals were tested against years (Fig. 5). Besides, relative yield residuals (relative to predicted values) were highly variable among countries and years, ranging from 0 to 60%, and did not show a decreasing trend over time. Among the major producing countries, Australia showed the lowest yield stability whereas China seemed to have reached high yield stability in the last 10 yr. Although it is difficult to assess the causes of variability between countries, weather restrictions are probably the most important modulators. Thus, the lowest yield stability observed in Australia could be mainly associated with the rainfall variability (Salisbury and Wratten, 1999) instead of low use of inputs or deficient agronomical practices. In relation to the hypothesis that stated that the higher harvested area determine lower yield variability, it seems to be true for China, India and Canada, the three largest global oilseed producing countries (Fig. 6A). When yield stability at country level is analyzed over the time, increases in harvest area could determine buffer effects as high and low potential regions area involved. At a country scale, this trend may be different when particular areas within each country are considered, especially if the increase in the harvested area involves incorporating marginal land with lower yield potential.

Yield stability does not appear to be associated with the country's experience in growing rapeseed, since European countries with a long tradition had similar residual values with respect to Latin American countries with considerably less experience with this crop. Thus, the results indicate that rapeseed yields have remained unstable over the past 40 yr, despite breeding and deeper knowledge attained on crop management. This behaviour contrasts with wheat, which exhibited lower relative residuals (0–30%) and greater yield stability in recent decades for several countries (Calderini and Slafer, 1998).

In many production systems, rapeseed strongly competes with other winter cereals such as wheat and barley. Thus, rapeseed competitiveness with respect to those other cereals is an important reason for farmers to adopt rapeseed for crop rotation. The wide range of data analyzed in the present study showed that relative rapeseed yield ranged 40–120% of wheat yield, but the variability in relative yield tended to decrease in high potential environments (wheat yields >4000 kg ha^{-1}), where it reached 40–50% of wheat yield (Fig. 8). Such values are remarkably consistent with those observed by Holland et al. (1999) for environments in the southern wheat belt and subtropical regions of northern Australia, representing a reliable general rule to assess rapeseed yield prospect. Part of this response is associated with an increased energy cost of rapeseed grains with respect to wheat, since the energy cost of oil is 125% greater than that of starch or protein, and 45% more assimilates are required to produce each gram of oil-rich seed compared with green biomass (Sinclair and de Wit, 1975). A proper comparison would require the adjustment of yields in terms of energy costs in both species, but, unfortunately, the FAOSTAT database does not provide national grain composition averages. However, an exercise was made considering the bottom line of rapeseed yield in Fig. 8 (0.4 of wheat yield), the energy cost to produce carbohydrates and oil (*i.e.* 1.242 and 3.106 g glucose/g, respectively, according to Penning de Vries et al., 1983), and three different rapeseed grain oil contents (30, 40 and 50% oil) were assumed. The exercise indicated that the rapeseed yields that were adjusted by energy were always lower than the adjusted wheat yields (0.6–0.7 of wheat yield, increasing the higher the oil grain content). Thus, the differences in the energy cost between both species explained only partially the differences in grain yield per unit area. Other attributes related to the different efficiencies in the capture and use of the resources could underline the differences between species, especially the lower photosynthetic capacity of green tissue post flowering in rapeseed (Mogensen et al., 1997; Sylvester-Bradley et al., 2002).

Regarding wheat environments in poor conditions where wheat yields are not higher than 2000 kg ha^{-1}, rapeseed yields became much more variable, but retained a minimum yield of 40% respect to wheat, and in half the cases, rapeseed even reached yields that were comparable to wheat ($\geq$70% of wheat yield), suggesting that its competitiveness is higher in poor environments (Fig. 8). Although the reasons for the better rapeseed performance with respect to wheat must be investigated, it is possible to speculate that in poor environments, where rain availability during the crop cycle is poor, rapeseed may yield better than wheat due to a higher capacity to capture water and/or to use water more efficiently than wheat. In Australian regions, with scarce and variable rainfall, comparative advantages in water use for rapeseed have been reported. In those regions, rapeseed showed an ability to restart growth and recover from an earlier period of water stress after rain reductions, reporting a higher ability to extract more water from deeper soil profiles than wheat, determining a relative insensitivity to drought during pod ripening and grain filling (McConkey et al., 2001; Holland et al., 2003; North, 2007; North et al., 2008; Liu et al., 2011a,b).

In conclusion, rapeseed yields have increased steadily in the past 40 yr in most studied countries, although the yield gain was not accompanied by greater yield stability. Competitiveness of rapeseed yield compared to wheat is at least 40–50% in environments with a good supply of resources, but may be even higher in poor environments. The lower efficiency of rapeseed over wheat remained even after correcting yield for the energy cost of producing oil. Clearly, improved resource capture and its partition to grain are major challenges for rapeseed improvement in the coming years.

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