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Gaps between farmer and attainable yields across rainfed sunflower growing regions of Argentina

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ABSTRACT

We computed three estimators of attainable yield for each of between 5 and 8 rainfed sunflower-growing regions of Argentina using between 5 and 9 years of data over the 2000–2007 interval. The estimators were based on comparative yield trial (CYT) data for commercial hybrids, on individual commercial field (ICF) data, and on reporting district (RD) yield information. Contrasts between these estimators led us to prefer the attainable (CYT) yield estimator over the other two. Attainable (CYT) yields ranged from 2.21 to 2.83 t ha^{-1} across regions. Yield gaps between mean farmer (RD data) and attainable (CYT) yields were computed using best linear unbiased estimator (BLUE) values for both variables obtained using mixed linear models. These gaps were statistically significant ($p \leq 0.05$) for all 8 regions and ranged from 0.37 to 1.18 t ha^{-1} across regions, for a country average of 0.75 t ha^{-1}, equivalent to 41% of the mean country yield of 1.85 t ha^{-1}. We also used CYT data to examine the issue of recurrent, albeit infrequent, reports of unusually high yields. Mean yields for the top decile of comparative yield trial data ranged from 3.2 to 4.2 t ha^{-1} across regions, and the highest yields for this decile in any of the years of record ranged from 3.9 to 4.8 t ha^{-1} across regions. Individual commercial field yields were available for 5 regions. Gaps between BLUEs for this variable and attainable (CYT) yields were smaller than those between reporting district and attainable (CYT) yields, but were nevertheless significant in all 5 regions. A notable feature of reporting district, individual field, and yield trial data was their variability. At reporting district level within regions, contributions of spatial and temporal variability were roughly similar. The mean relative contribution of the trial effect to non-error variance of the CYT data exceeded 85% across regions, dominating the contributions of genotype and of genotype by trial effects. We conclude that the magnitude of mean farmer/attainable (CYT) yield gaps for this crop in Argentina justifies further research aimed at reducing regional gaps; and that CYT data can be used to generate an appropriate benchmark for attainable yields.

1. Introduction

The yields obtained by farmers for several crop species and in many cropping systems around the world have almost always been shown to be lower than those attainable using locally optimised agricultural best practices and adapted, current, cultivars (e.g., Cassman, 2010; Fischer et al., 2009; Fischer and Edmeades, 2010; Lobell et al., 2009; Aggarwal et al., 2008; Laborte et al., 2012). Attainable yield (Yatt) is a context-dependent variable that is affected by environmental, economic and sociological factors. Provided this is understood, it constitutes an appropriate benchmark in yield-gap analysis. It should be noted that Yatt in rainfed systems is not the same as water-limited yield (Yw, as defined in Van Ittersum et al., 2013), although for a given region it may approximate the latter if local good farming practice approaches optimal practice. In this paper, we use Yatt as defined in Fischer and Edmeades (2010) and Fischer et al. (2009) and, following these same authors, we estimate yield gaps as the difference between mean farmer and attainable yields.

Abbreviations: Yatt, attainable yield; BLUE, best linear unbiased estimate; CI, confidence interval; CRF, cumulative relative frequency; CYT, comparative yield trial; ICF, individual commercial field; MLM, mixed linear model; RD, reporting district; REML, restricted maximum likelihood; Top10, mean, across years, of CYT values included in the top decile of the corresponding cumulative relative frequency distributions; ULRY, upper limit to rainfed yield; Yw, water-limited yield.

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Most yield-gap analyses have focussed on the main cereal food grains (rice, wheat, maize), although Aggarwal et al. (2008) also looked at these gaps for cotton and mustard. These yield gaps can be substantial. Expressed as a percentage of current farmer yields, Fischer et al. (2009) and Fischer and Edmeades (2010) cite many cases of gaps of between 45% and 100%. Data compiled by Lobell et al. (2009), expressed on the same basis, are broadly consistent with this range, although their list includes a number of examples of gaps in the 100–200% range or even higher.

The demonstration of important yield gaps for particular crops and cropping systems provides an essential framework within which to prioritize research and policy efforts aimed at reducing these gaps (e.g., Tittonell et al., 2008; Aggarwal et al., 2008; Abeledo et al., 2008; Laborte et al., 2012). It is acknowledged that yield gaps cannot be reduced to zero due to widespread practical and economic constraints applying to commercial farming (Fischer et al., 2009). Empirical analyses suggest minimum limits to gaps of 20–25% of current farmer yield (Fischer et al., 2009) or 20% of potential (or water-limited yield in rain-fed systems) yield (Lobell et al., 2009). In a few very intensively managed systems (rice in Egypt, Fischer et al., 2009; irrigated maize in the Western US cornbelt, Grassini et al., 2011a,b), yield gaps may be approaching (or have actually fallen below) these estimated minima.

Various approaches have been suggested or used for estimating yield gaps (cf. Fischer et al., 2009; Lobell et al., 2009; Aggarwal et al., 2008; Licker et al., 2010; Abeledo et al., 2008; Grassini et al., 2011a,b; Laborte et al., 2012). Each of these approaches has particular advantages and disadvantages. Farmer yields have been estimated using regional or national statistics, and by sampling farmers' fields, either directly or using remote sensing (Lobell et al., 2007, 2010). Attainable and potential yields have been estimated using on-farm experiments, yield contest results, research station experiments, crop models, and breeders' trials. Licker et al. (2010) and Gerber et al. (2010) have proposed a system based on a detailed analysis of regional statistics. In their procedure, regions across the globe are classified into a limited number of bins (defined by combinations of duration of growing season and an index of water availability) and reported yields within each bin are sorted to identify the 95th percentile value, which is taken as an Yatt for that bin.

The temporal and spatial scales across which quantification of yield gaps has been attempted has varied widely. Explicit consideration of temporal variations in yield gaps, something which can be particularly important in rain-fed systems, has received little attention, save when models or remote sensing have been used to analyse extended estimated yield or climatic records (e.g., Lobell et al., 2007; Abeledo et al., 2008). In the spatial dimension, yield gap estimation has covered the ranges from local (e.g. the Yaqui and Ebro valleys, Lobell et al., 2009; Abeledo et al., 2008) through to regional (Grassini et al., 2011a,b; Lobell et al., 2010; Laborte et al., 2012), national or mega-environment (Fischer et al., 2009; Aggarwal et al., 2008), and on to global scales (Licker et al., 2010; Gerber et al., 2010).

Here we report the results of a yield gap analysis for the sunflower growing regions of Argentina. The analysis was conducted on behalf of the Asociación Argentina de Girasol (ASAGIR), the Argentine sunflower value chain association. The objective was to quantify the magnitude of the farmer/attainable yield gap for this crop, and its temporal and spatial variability. ASAGIR wished to determine whether the size of current yield gaps justified further research into yield gap reduction. ASAGIR was also seeking a framework which would allow infrequent, but recurring, reports of high grain yields (4–5 t ha^{-1}) to be placed in the context of national yield averages in the order of 1.7–1.9 t ha^{-1} (sunflower yields are usually reported at 11% moisture content). Distinctive features of our analyses are that they apply to rainfed crops (irrigated sunflower crops in Argentina are usually only used for hybrid seed, as opposed to grain, production) of current commercial hybrids, they cover eight separate regions of the country, the data for the most important crop-reporting districts within each region were used to estimate farmer yields, and the number of years considered ranged between 5 and 9 according to region.

We used three different methods to estimate Yatt, based on data from comparative yield trials (CYT), from individual commercial farmers' fields (ICF), and from crop-reporting districts (RD) (see Section 2.3). To the best of our knowledge, our analyses are the only country-wide exercise aimed at quantifying yield gaps for the sunflower crop and the one of the very few (cf. Aggarwal et al., 2008) in which several techniques for estimating Yatt for a given crop are compared.

Comparison of the three estimates of Yatt described above led us to select the CYT-based estimate as the most useful for our purpose. Using this estimator, we computed farmer/attainable yield gaps, and their regional and temporal variation. We also explored the magnitude and variability of the highest yields achieved in the CYTs. Our interest here was to provide a quantitative overview, across years and regions, of unusually high yields. This overview provides a reference framework in which to place the recurrent, but infrequent, reports of very high yields for the crop. Reports of this type often feature in advertisements for seeds and in discussions between farmers skilful enough or lucky enough to achieve these unusually high yields.

2. Materials and methods

2.1. Regionalisation

Sunflower is grown extensively in several distinct agroecosystems in Argentina, which are distinguished by seasonal rainfall, radiation and temperature patterns; soil properties (texture, soil depth, organic matter content); the role of sunflower in the cropping system (sole within-season crop, lead crop of a seasonal sequence of two crops); and crop management (time of sowing). Several approaches have been used to classify this diversity. Breeders, for example, distinguish Southern, Central and Northern regions (e.g., de la Vega and Chapman, 2010). By contrast, the Buenos Aires Grain Exchange (Bolsa de Cereales de Buenos Aires, 2011) distinguishes, for the area in which sunflower is grown, 12 grain-crop reporting districts, based on several main crops for each district. A further dimension to this issue is that yield-reporting districts for national statistics are based on departmental, rather than biophysical, boundaries. For the purpose of this analysis, a consensus set of eight regions was developed with input from breeders, farmers, and traders (Table 1 and Fig. 1).

Fuller details on soils, rainfall and temperature regimes for regions included in the Pampas (i.e., all regions listed in Table 1 except NEAR) may be found in Hall et al. (1992). Briefly, important SE to NW gradients across the Pampas region reflect increasing temperature and rainfall, and a gradation in soil texture from coarse to fine. Petrocalcic layers limit soil depth in the SEBA region, and annual rainfall distribution in this region is almost isohygrous, in contrast to the summer-dominant patterns for the remaining Pampean regions. Petrocalcic layers are also a feature in some soils of the SLLP region, but these layers tend to be deeper in the profile than those of the SEBA region. Sunflower is grown as a sole crop within a season across all the Pampean regions, with sowing date occurring later from N to S. Chapman and de la Vega (2002) have described weather (rainfall, temperature) conditions for the NEAR region. Soils in the NEAR region are fairly heterogenous, but lighter and deeper soils are more frequent in the W of this area, and shallower and heavier soils in the E (Mosconi et al., 1981; Ledesma

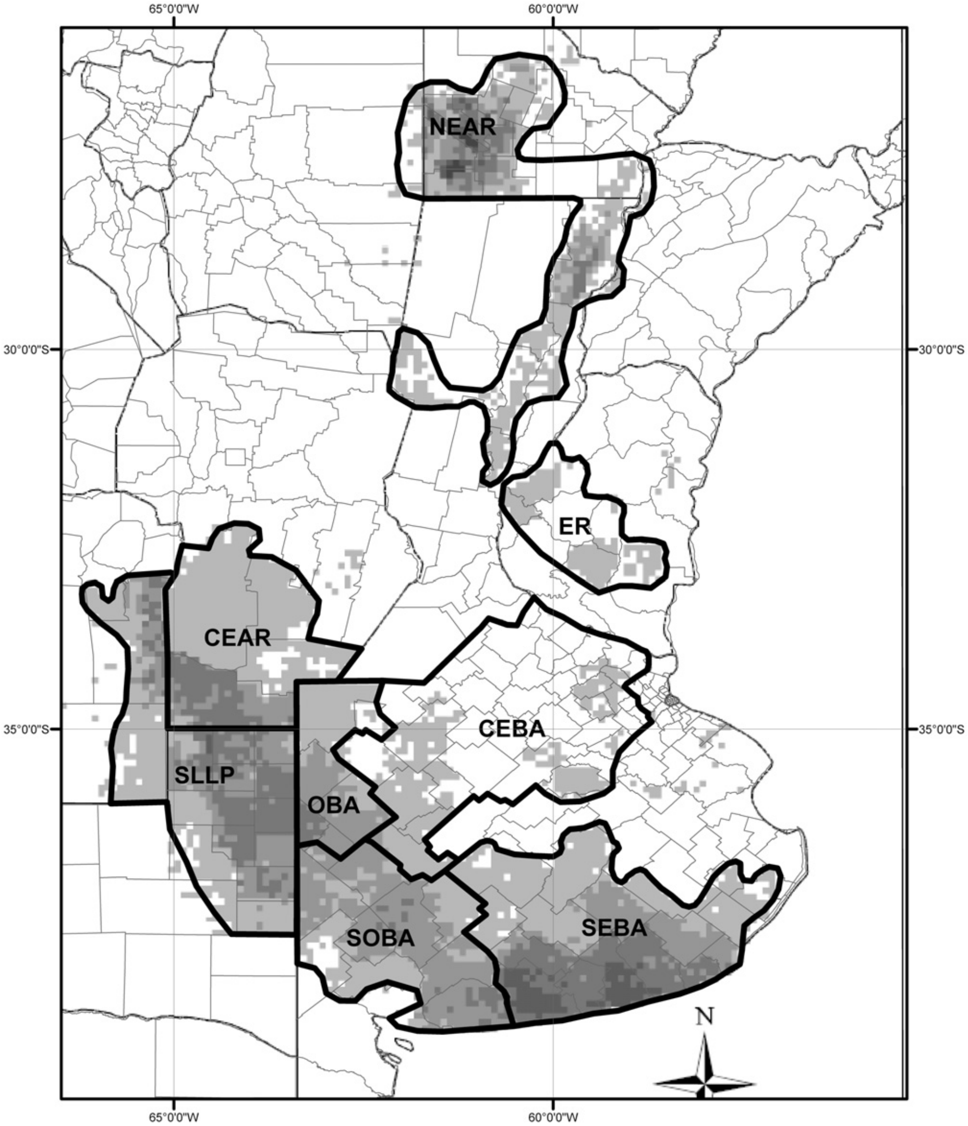

Fig. 1. Distribution of area cropped to sunflower in Argentina ca. 2000. All 10 km^2 pixels with >1% of the surface sown to sunflower are shown. Increasing % sunflower area within a pixel, darker grey. Data source: Portmann et al. (2009) based on Monfreda et al. (2008). Data mapped by Grassini (pers. comm., 2009), Univ. of Nebraska-Lincoln. Reporting district limits are in thin lines, provincial boundaries are in lines of intermediate thickness, and regional limits are in thick lines as mapped by G. García Accinelli (pers. comm., 2010), LART-FA Univ. Buenos Aires. For acronyms for sunflower growing regions, see Table 1.

and Zurita, 2004). In this region crops are sown and harvested earlier than the remaining ones (August–September vs. October; December vs. February–March), and waterlogging can be a significant constraint in high-rainfall (Niño) years (Chapman and de la Vega, 2002). Provided early season rains are sufficient, sunflower can act as a lead crop for a sequence of two crops within a season in the NEAR.

Farm size varies across regions although definitive statistics are hard to come by. Mean farm sizes reported in the 2002 census (the latest available with data on a reporting district basis) was greatest (1670 ha) in the SLLP reporting districts used in this study, between 600 and 770 ha in the appropriate RDs for the OBA, SEBA, SOBA and CEAR regions, and smallest (300–490 ha) in the appropriate RDs for the ER, CEBA and NEAR regions (Instituto Nacional de Estadísticas y Censos, 2002). Effective land surface farmed by a specific farmer or farming enterprise may be greater than these mean values due to widespread use of rented land. In addition, these mean values may also be affected by a steady trend towards farm consolidation, especially in the provinces of Buenos Aires (which includes SEBA, SOBA, OBA and CEBA regions) and Entre Ríos (ER region). Between 2002 and 2008 farm number in Buenos Aires dropped by 38% and in Entre Ríos the drop was 18%. In other provinces that are included in other sunflower-growing regions, farm consolidation took place more slowly with reductions in the number of farms of between 0% and 7%.

As with any attempt at regionalisation, excessive simplification and excessive sub-division are dangers to be avoided. We believe that the use of eight regions provides a reasonable, although admittedly not perfect, approximation to the diversity in climate, soils and management of the current sunflower-growing areas of Argentina.

2.2. Data sources

2.2.1. Source of farmer (reporting district) yield data

Yields for RDs making the greatest contribution to the total yield of each region (between 2 and 6 districts per region) over the 1999–2007 period were obtained from the Agriculture Ministry database (Ministerio de Agricultura, 2011) and used as estimates of average farmer yields in each year and region. Harvested area per

Table 1
Annual means for cropped area and total production for consensus regions for sunflower-growing in Argentina, 2000–2007. Acronyms for regions, as used in the text, are shown in brackets in the region column. Geographical extent and limits to regions are shown in Fig. 1.

Region	Area cropped with sunflower (ha) and (% of national total)	Total sunflower production (t) and (% of national total)
South East Prov. of Buenos Aires (SEBA)	654,642 (29.1%)	1,096,471 (28.4%)
South West Prov. of Buenos Aires (SOBA)	344,193 (15.3%)	540,514 (14.0%)
West Prov. of Buenos Aires (OBA)	114,731 (5.1%)	181,458 (4.7%)
Center Prov. of Buenos Aires (CEBA)	94,484 (4.2%)	204,623 (5.3%)
San Luis and La Pampa Provinces (SLLP)	395,935 (17.6%)	660,200 (17.1%)
Central Argentina (CEAR)	213,715 (9.5%)	440,133 (11.4%)
Entre Ríos Province (ER)	47,242 (2.1%)	77,216 (2.0%)
North East Argentina (NEAR)	384,687 (17.1%)	660,200 (17.1%)
National totals	2,249,630 (100.0%)	3,860,816 (100.0%)

year and region varied between 15,000 and 500,000 ha, and total sampled harvested area for the eight regions represented about 1,200,000 ha or about 50% of total national harvested area for the 1999–2007 period. This degree of coverage was expected to provide reasonable estimates of mean farmer yields per year and region.

2.2.2. *Sources of individual commercial field yield data*

Data for yields in ICFs were available for a total of 5708 fields in five of the eight regions (i.e., CEAR, SEBA, SOBA, OBA, SLLP) for periods of between six and nine years during the 1999–2007 window. The majority of data on yields in ICFs were provided by farmers who are members of AACREA (Argentine Association of Consortia for Regional Agricultural Experimentation) (81% of the total) and by a commercial firm specialising in grain production on rented fields (Cazenave & Asoc.) (19% of the total). Both groups use knowledge-intensive management practices and sow current commercial hybrids. Fields ranged in size from 40 to 150 ha, and most of them were managed using conservation agriculture.

2.2.3. *Sources of comparative yield trial data*

Data for the CYT database was provided by the INTA-ASAGIR testing network and by private seed companies (Asociación de Cooperativas Argentinas ACA S.A.; Advanta S.A.I.C.; Asociados Don Mario S.A.; Dow AgroSciences Argentina S.A.; Monsanto Argentina S.A.I.C.; Nidera S.A.; Pannar Semillas SRL; Profertil S.A.; SPS Argentina). Table 2 lists a set of hybrids that are representative for the 2000–2007 period. It is important to note that over that interval there was a slow but steady turn-over of hybrids included in the multi-environment trials.

Trials of the ASAGIR-INTA testing network are conducted, in about equal proportions, on INTA research stations and farmers fields. A limited number of the yield trials conducted by seed companies are located on their own research stations, but the majority is conducted in farmers' fields across the sunflower growing area. These latter trials are run as islands (area 0.5–10 ha) within much larger fields (area from 40 to 120 ha) usually, but not always, cropped to sunflower. The number of entries in a seed-company yield trial can vary between 15 and 75–100, but here we only used the data for the commercial hybrids included in each trial. Experimental designs vary between companies, ranging from unreplicated to replicated designs, but almost all trials are conducted using plot sizes larger than 3 rows by 6–7 m, overseeded and later thinned to close to commercial crop population densities (ca. 5 pl. m^{-2}). Yield estimates are obtained harvesting the central row(s) of each plot, and are reported at 11% moisture content. An important distinction between commercial seed company trials and those of the ASAGIR-INTA testing network is the number of commercial hybrids included in each trial (average for seed companies 15, average for INTA-ASAGIR trials 40). Both groups of yield trials are audited (internally by seed companies, INTA-ASAGIR trials by an independent expert), and deficient (i.e., damaged by hail, poor emergence, etc.) trials are discarded. As noted above, there is no one single protocol followed by all involved in setting up and running yield trials but there is a great deal of consensus on aims and procedures, and differences between good farmer practice and yield trial management are small. Sowing dates are as close as possible (rain permitting) to the optimum for each region. Levels of fertiliser application are almost always very similar (breeders attempt to follow farmer practice, and do not aim to demonstrate the advantage of applying fertiliser to meet soil-test levels), herbicide management (compounds, doses, frequency) is indistinguishable, stand homogeneity in trial plots is no better than can be achieved by farmers using pneumatic seeders, good farmers use seed pre-treated with the same compounds as those applied to seed used in trial plots. If trials are hand planted then this is done in the furrows made by the farmer's planting rig, otherwise a small planter with similar tillage implements to that of the farmer is used in the plots. Selection of fields for use in trials follow the same principles a good farmer would use (e.g., sufficient years since last sunflower crop, inferred weed seed bank, preceding crop, effectiveness of pre-planting fallow, etc.). Trials are normally visited only 3–5 times during the growing season, and insecticides (when required) are applied by the farmer who is managing the field in which the trial is established. Harvest efficiency may be higher in the plots, but not much greater than that of a demanding farmer who is closely supervising his harvest to avoid losses through excessive rig speed or inappropriate winnowing adjustment.

Table 2
Representative hybrids for the 2000–2007 period (seed-producing companies in brackets after each hybrid). All hybrids listed were widely sown, although not necessarily in all eight regions defined in this paper.

ACA 884 (Asoc. Coop. Argentinas)
CF 17 (Advanta)
DK 3820 (Monsanto)
MG 2 (Dow Agrosciences)
NK 254 (Syngenta)
SPS 3130 (SPS)
Pannar 7031 (Pannar)
Paraiso 20 (Nidera)
Zenit (Sursem)

The multi-environment trial database used in this study, after filtering (see below), and averaging across replicates contained a total of 646 field trials including 11,411 entry means, one for each hybrid in each trial. Trials were assigned to regions on the basis of location. The database for each year and region was restricted to trials that included at least 7 commercial hybrids (including at least two entries from competing companies). To qualify for inclusion in the yield trial database for each region, only years with 5 or more trials were considered. As a result of the application of these filters, estimates of Yatt were obtained for between 5 and 9 years (within the 1999–2007 interval) for the various regions. Importantly, the regions that contribute most to the annual national crop (SEBA, OBA, SLLP, NEAR, SOBA) all had 6–9 years of records.

2.3. *Estimates of attainable yield*

2.3.1. *Estimates based on comparative yield trial data*

An estimate of Yatt for each year and region was derived from data obtained in multi-environment CYTs of commercial hybrids (see Section 2.2.3) using mixed linear models (see Section 2.5). In what follows, this estimate is labelled attainable (CYT) yield.

2.3.2. *Estimates based on individual commercial field data*

Following an approximation similar to that used by Laborte et al. (2012), the mean of the data included in the top decile of the cumulative relative frequency curve for individual commercial field yields (see Section 2.2.2) for each year by region combination was used to obtain an estimate of Yatt for that year by region combination. In what follows, we term this estimate attainable (ICF) yield.

2.3.3. *Estimates based on reporting-district data*

Information from the RD database (see Section 2.2.1) was used to generate a regional estimate of Yatt following an approximation similar to that used by Licker et al. (2010), by taking the 95% percentile of the cumulative relative frequency curves for all RD yield estimates across all years within a region (see Fig. 4 for examples of this). Values for this estimate, referred to hereafter as attainable (RD) yield, are shown as single values for each region.

2.4. *Quantification of very high yields in CYTs*

We did this in two ways. First, we estimated the mean value for the best 10% of yields obtained in comparative yield trials in each year by region combination, a metric we termed Top10. Second, we identified the greatest Top10 value obtained in each region across all years of record, which we refer to as the upper limit to rainfed yield (ULRY).

2.5. *Statistical analyses*

No attempt was made to adjust data included in any of the three data-bases (i.e., RD, ICF and CYT) for rates of gain in Yatt over the period considered in these analyses. de la Vega and Chapman (2010) have shown that gain in sunflower oil Yatt over a recent 18-y period in Argentina has been of the order of 7.8 kg oil $\text{ha}^{-1}\,\text{y}^{-1}$ (mean of Northern, Southern and Central regions), or about twice that value in terms of kg grain $\text{ha}^{-1}\,\text{y}^{-1}$ (assuming a mean oil content of 50% and ignoring the possible trade-off between grain oil content and yield). Over the longest period (9 y) considered in our study for any of regions, this gain would have represented a value of the order of 144 kg ha^{-1}, small in contrast to our estimates of standard deviations (SD) for spatial and temporal variability of farmers' yields, which were of the same order (or greater) than mean farmer yield (ca. 1.8 t ha^{-1}) across all regions (see Section 3.4). A further reason for ignoring possible effects of temporal bias due gain in Yatt is the finding (de la Vega et al., 2001), in an analysis of an extended series of trial results for the Northern and Central sunflower-growing regions of Argentina, that effects of environment (E) accounted for 87% of the non-error variance for oil yield. Of the remaining variance, the G × E interaction was 3.1 times that of the contribution of G. Our results (see Section 3.4) are consistent with these findings.

Data for farmer (RD), ICF, and CYT yields were summarized by means of the best linear unbiased estimator (BLUE) of annual yield derived from mixed linear models (MLM, Littell et al., 2006) fitted to data for each crop region within each database using SAS PROC MIXED version 9.3 (SAS Institute, 2006). All MLM variance parameters were estimated by restricted maximum likelihood (REML, Patterson and Thompson, 1971). In the case of the CYT database the MLM analytical approach was chosen to estimate variance components because it accounted for incomplete data across years (due to temporal changes in hybrids), varying number of hybrids across trials, and different amounts of information per hybrid (Schabenberger and Pierce, 2002). In the ICF and the RD databases, locations represented a selection from a population cropped to sunflower, and the number of yield reports varied across years and between regions. Use of the MLM approach allowed us to deal with random components and these imbalances.

To estimate annual farmer (RD) and ICF yields realised in each year we fitted a MLM that considered year as a fixed effect and location within year as a random effect for each region in the RD and ICF databases, respectively. Year effect was regarded as fixed because of the need to estimate average yield for specific (i.e., other than random) years. Location effects were treated as random because they are a sample of locations within the region. Resulting BLUEs of annual yields were used to estimate the expected value for farmer and individual field yields in each region. The significance of differences between mean annual farmer and mean individual field yields with respect to attainable (CYT) yields within each region was determined by means of a paired t test, with a significance level of 0.05.

A second MLM was fitted to the RD database to estimate temporal and spatial yield variability in farmer (RD) yields. This MLM considered year and location within year as random effects, thus allowing separation of these two sources of variability. Farmer (RD) temporal yield variability was estimated as the between-year variance component, and the variance parameter estimating variability among locations within a year was used to infer spatial variability in farmer (RD) yield.

A third MLM fitted to the CYT database to estimate attainable (CYT yields was specified considering year as a fixed effect and several random effects: trial nested within year, hybrid, hybrid-by-trial interactions, as well as an extra term for residual variability due to differences among replicates within a trial. As in the other databases the year effect was treated as fixed to obtain estimates of attainable (CYT) yield for the selected years, and the other effects treated as random to take into account the variability and correlations imposed on data from different trials and hybrids. Additionally, and in order to estimate the relative importance of each variance component of CYT variability, a MLM with trial, hybrid, hybrid-by-trial random effects was fitted year-by-year within each region. The resulting non-error variance within each year and region was partitioned into the contributions (in percent of total non-error variance) of trial, hybrid and hybrid-by-trial interaction components.

Graphical representations of yield variability across hybrids within each individual trial were generated using a cumulative relative frequency (CRF) curve for the hybrid entry means for each trial; and these were displayed as a set of CRF curves for each year and region, generating a total of 57 year by region displays. A representative illustration of these year-by-region CRFs is shown in Fig. 2. Another metric extracted from the CYT database was an estimate, for each year and region, of the mean yield for the top decile of trial results (Fig. 2). This metric, which we term Top10, can be regarded as an estimate of the upper yield limit for each year and region. Across all available data-years for each region, the highest observed Top10 in the series was identified. We term this value as the upper limit to rainfed yield (ULRY). These metrics were used to quantify the magnitudes of unusually high yields.

Among-region contrasts of farmer (RD), attainable (CYT), mean ICF, attainable (ICF) and Top10 yield annual BLUEs was performed by using ANOVA and the LSD test ($\alpha = 0.05$). In order to test the significance of differences between attainable (CYT) yields and the other metrics within each region, a paired *t* test was used. No tests of significance of inter-regional differences in attainable (RD) yield and in ULRY were performed because quantile standard errors were not available.

Mean farmer/attainable (CYT), and mean individual commercial field/attainable (CYT) yield gaps were estimated for each year and region as the difference between the corresponding BLUEs of annual yields. Means of these yield gaps, as well as their 95%

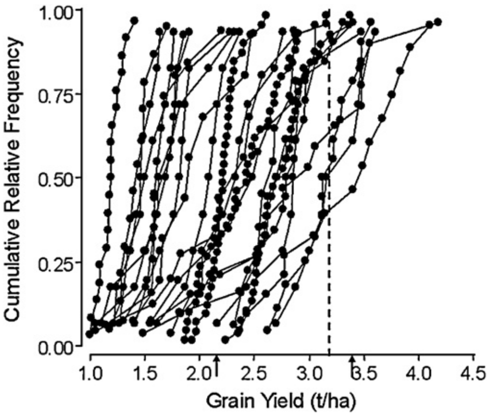

Fig. 2. Example (NEAR region in 2006) of cumulative relative frequency plots for a set of comparative yield trials. Each data point is a single hybrid, each cumulative relative frequency plot a single trial. Vertical arrows on the abscissa indicate: the mean BLUE (i.e. the attainable (CYT) yield estimate for that year and region) for whole data set (left-hand arrow) and the mean BLUE for Top10 (right-hand arrow) estimate for that year and region. The vertical dashed line separates the data points included in the Top10 estimate from the remainder.

confidence intervals, were obtained by the bootstrap method (Balzarini et al., 2008), and paired t tests were used to assess their statistical significance ($\alpha = 0.05$).

3. Results

3.1. Measures of attainable yield

A comparison between the three estimates of Yatt generated in this analysis (Table 3) shows that over the five regions for which we were able to quantify attainable (ICF) yield estimates, these were statistically indistinguishable from the CYT estimate in three regions and greater than the CYT estimate in two others. This is important because it strongly suggests that the CYT estimate for Yatt is conservative and that it does not reflect especially favourable environments and/or management procedures in the variety trials that would make for unrealistic contrasts with production agriculture conditions. The attainable (RD) yield fell below the lower 95% confidence limit of the attainable (CYT) estimate for the SEBA, SOBA and OBA regions (data not shown) and was between the upper and lower CYT confidence limits in the remaining five regions. In addition, in the SEBA region, the RD estimate fell below the lower 95% confidence limit of the attainable (ICF) estimate (data not shown). These results are not surprising given that attainable (RD) values are derived from means across whole reporting districts, while CYT and ICF estimates reflect means of point values or the best yielding fields in each year by region combination, respectively. Given the greater regional coverage of the CYT estimates, the greater number of observations in the CYT vis-à-vis the ICF regional databases for all regions except SEBA, and the indications that the RD estimate tends to undervalue attainable yields, we will hereafter use the CYT estimate as the best available indicator of Yatt.

3.2. Mean farmer (reporting district), attainable (CYT), individual commercial field and Top10 yields

Attainable (CYT) yields were significantly greater than mean farmer (reporting district) yields in all eight regions (Table 3), at significance levels of $p < 0.01$ and $p < 0.001$ for the four regions (SEBA, SOBA, SLLP and NEAR) that produced 79% of the mean national sunflower grain harvest (Table 1). Attainable (CYT) yields were also significantly greater than mean ICF yields in all five of the regions for which ICF data was available (Table 3). In seven of the eight regions mean Top10 yields (i.e., our measure of especially high yields derived from the CYT database) were 40% or more greater than corresponding attainable (CYT) yield estimates, and these differences were highly significant for all eight regions. ULRY (highest recorded Top10 for each region across years) values were in the 3.9–4.8 t ha^{-1} range across regions, and were rather similar among regions except for ER (Table 3). ULRY values significantly exceeded Top10 estimates for all regions (($p < 0.001$) for all regions except OBA, for which the significance level for the difference was $p < 0.05$). Some of the differences between regions in farmer, attainable, individual field and Top10 yields were also significant (Table 3).

The differences between mean farmer (RD), attainable (CYT), and Top10 yields, and – in three of the four regions – the mean ICF yields are further illustrated for the four regions contributing most to the national harvest by the CRF curves for these variables (Fig. 3). Although data points in each panel of this figure do not necessarily line up simultaneously on the “y” axis and in the temporal dimension, systematic review of all the data showed that mean farmer (RD) yields were consistently lower than the corresponding attainable (CYT) yields across all regions and years except for 2006 and 2007 in the ER region. Similarly, mean ICF yields (in regions and years with available data) were lower than mean attainable (CYT) yields across all regions and years except for 1999 and 2007 in SEBA and for 2005 in CEAR. Fig. 3 also serves to confirm that Top10 yields were consistently greater than attainable (CYT) yields. In all three regions with data for individual field yields shown in Fig. 3, these yields were greater than farmer (reporting district) yields, but this was not the case in the CEAR and OBA regions, in which individual field yields tracked reporting district yields very closely (data not shown, but see Table 3).

3.3. Mean farmer (RD)/attainable (CYT) yield gaps

Mean farmer (RD)/attainable (CYT) yield gaps across the regions were in the 0.4–1.2 t ha^{-1} range (Table 4), which translated into 0.75 t ha^{-1} at a country level, a substantial value when contrasted with a national mean yield of 1.85 t ha^{-1} (Table 3). Importantly, the gap was close to or greater than 60% of farmer yields in three (SEBA, SOBA, SLLP) of the four regions that contribute most to the national sunflower harvest (Table 4). The absolute magnitude of the mean farmer (RD)/attainable (CYT) yield gap varied among regions (Table 4), but the significance of these inter-regional differences was limited, with the exception of SEBA (gap significantly greater than that of five regions) and ER (gap significantly smaller that that of four regions). Of the four regions contributing most to the national harvest, the magnitude of the gap was statistically indistinguishable between SEBA, SOBA and SLLP, while NEAR exhibited a significantly smaller gap than the remaining regions in this quartet. The relative magnitude of the gap, expressed as a percentage of the mean of ICF yields, was smaller than the gaps estimated on a RD basis in SEBA, SOBA and SLLP, but remained more or less at the same level in OBA and CEAR. The only significant inter-regional difference in the size of the gap at ICF level was that between SOBA (lower) and OBA (higher).

3.4. Spatial and temporal yield variability

An important feature of all three databases (i.e., RD, ICF, CYT) was variability in yields within each region and year. Reporting district variability is illustrated for four regions in Fig. 4, and estimates of the spatial and temporal components of the corresponding variances are given in Table 5. Whether viewed as the resultant of the combined effects of spatial and temporal variability within a region, as reflected in the minimum–maximum yield range (greater than 1 t ha^{-1}) (Fig. 4), or partitioned into spatial and temporal components (Table 5), yield variability was large in all regions. The

Table 3
Farmer (RD), individual commercial field, attainable (CYT), attainable (ICF), attainable (RD), Top10, and upper limit to rainfed yield (ULRY) yield estimates at region and country (where appropriate) levels. Values in cells of columns 2, 3, 4, 5 and 7 are means and SEM of BLUEs for annual yields. Dashes indicate cells for which scaling from regions to country would be inappropriate. Values in brackets in the "farmer yield (RD)", "individual commercial field (ICF) yield", and "attainable (ICF) yield" columns indicate number of years of data used to estimate annual yields. Numbers of years of data for attainable (CYT) and Top10 yields were the same as those for farmer (RD) yields. Values in brackets in the "attainable (RD)" column indicate number of county by year data points in the corresponding cumulative relative frequency distribution. Asterisks in the farmer (RD), individual commercial field (ICF), attainable (ICF), and Top10 columns indicate statistical significance of differences with attainable (CYT) yields ($^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$) for each region. Values within a single column followed by different letters are statistically different ($p < 0.05$).

Region	Farmer (RD) yield ($\mathrm{t\,ha^{-1}}$)	Individual commercial field (ICF) yield ($\mathrm{t\,ha^{-1}}$)	Attainable (CYT) yield ($\mathrm{t\,ha^{-1}}$)	Attainable (ICF) yield ($\mathrm{t\,ha^{-1}}$)	Attainable (RD) yield (95% value for CRF) ($\mathrm{t\,ha^{-1}}$)	Top10 yield ($\mathrm{t\,ha^{-1}}$)	Upper limit to rainfed yield (ULRY) ($\mathrm{t\,ha^{-1}}$)
SEBA	1.53 ± 0.07 (9)b ***	2.05 ± 0.08 (9)ab **	2.71 ± 0.12 bc	3.18 ± 0.12 (9)a **	2.00 (42)	3.89 ± 0.17ab ***	4.59
SOBA	1.59 ± 0.08 (6)b ***	2.13 ± 0.15 (6)ab **	2.56 ± 0.12 cd	2.57 ± 0.15 (6)c	2.19 (30)	4.15 ± 0.15a ***	4.82
OBA	2.21 ± 0.08 (7)a ***	2.15 ± 0.07 (7)a *	3.05 ± 0.12 a	2.99 ± 0.13 (7)bc	2.70 (35)	4.06 ± 0.24a ***	4.64
CEBA	2.25 ± 0.14 (7)a *	No data	2.83 ± 0.11 ab	No data	2.89 (18)	4.21 ± 0.15a ***	4.73
SLLP	1.61 ± 0.10 (7)b ***	1.89 ± 0.07 (6)b **	2.54 ± 0.18 cd	2.69 ± 0.15 (6)bc	2.30 (20)	3.98 ± 0.19ab ***	4.74
CEAR	2.13 ± 0.12 (8)a **	2.07 ± 0.09 (7)ab **	2.58 ± 0.08 bc	2.90 ± 0.15 (7)ab *	2.63 (14)	3.56 ± 0.16cd ***	4.22
ER	1.83 ± 0.16 (5)b *	No data	2.21 ± 0.17 de	No data	2.19 (15)	3.20 ± 0.23d ***	3.92
NEAR	1.69 ± 0.10 (8)b **	No data	2.22 ± 0.10 e	No data	2.17 (20)	3.63 ± 0.19bc ***	4.52
Country	1.85 ± 0.05	–	2.60 ± 0.05	–	–	–	4.82

temporal component of variance appeared to be especially high in the CEAR, ER and NEAR regions and rather low in SOBA and OBA regions; while the spatial component was low in the CEAR region (Table 4). With these exceptions, both components made substantial, and similar, contributions to total variance.

As shown by the scattergrams presented in Fig. 5, ICF yields showed substantial variation within each year as well as some tendency to shift the range of observed yields between years. Although mean individual commercial field yields were lower than attainable (CYT) yields in all regions for which individual field data were available (Table 3), yields on some fields exceeded the corresponding Yatt estimate for the year and region (Fig. 5), perhaps most notably in SEBA. In the CEAR region (data not shown) the relationship between these variates was similar to that shown for SOBA (Fig. 5). Across all years and the five regions for which ICF yield data were available, an average of 12.4% of individual commercial fields had yields greater than the corresponding region by year estimate for attainable (CYT) yield, by a mean margin of 8.8% of the appropriate attainable (CYT) estimate (data not shown). These results indicate that some farmers, in some of their fields, and in some years, can equal or better the mean yields attainable using good practice as embodied in the CYTs.

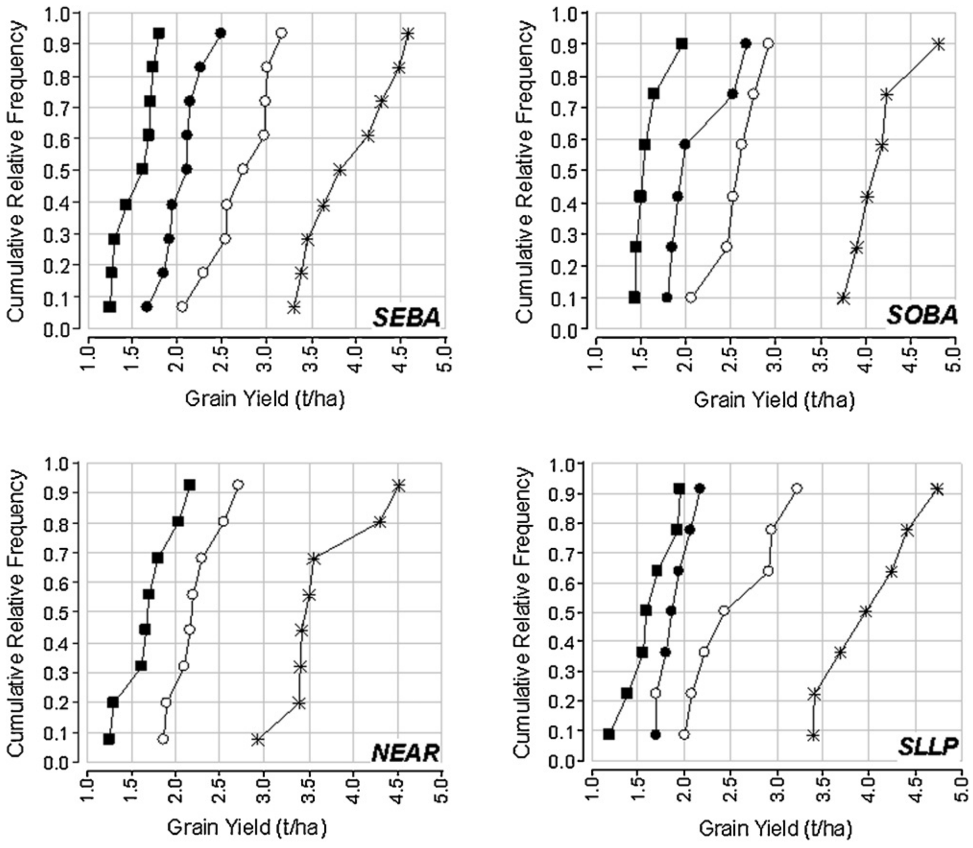

Fig. 3. Cumulative relative frequency curves for mean annual values for mean farmer (RD) yields (solid squares), attainable (CYT) yields (empty circles), mean individual commercial field yields (solid circles) and Top10 yields (asterisks) for four regions. In the individual field data plot for SLLP the empty symbol is a missing value estimate. All data points are BLUEs. Note that data points for a given year do not necessarily line up on the "y" axis across plotted variables (not shown); that individual commercial field yields were not available for the NEAR region; and that the number of years of data vary between regions (see Table 2).

Table 4
Absolute and relative (to the appropriate reference) farmer/attainable (CYT) and individual commercial field/attainable (CYT) yield gaps at region and country (where appropriate) levels. Yield gap and confidence interval (CI) estimates were obtained using bootstrap resampling of annual yield gaps. Dashes indicate cells for which scaling from region to country cannot be done. Values within a single column followed by different letters are significantly different ($p < 0.05$). Within-column tests of significance were performed using a separate mixed model (region: fixed effect, year: random effect) which allowed for the imbalance in number of years across regions and which yielded slightly different CI estimates to those shown in the table.

Region	Mean farmer/attainable (CYT) yield gap ($t\,ha^{-1}$) mean and (95% CI)	Mean farmer/attainable (CYT) yield gap as % of mean farmer yield	Mean individual commercial field/attainable (CYT) yield gap ($t\,ha^{-1}$) mean and (95% CI)	Mean individual commercial field/attainable (CYT) yield gap as % of mean individual commercial field yield
SEBA	1.18 (1.05–1.31)a	77	0.65 (0.38–0.88)ab	32
SOBA	0.98 (0.75–1.17)ab	62	0.43 (0.25–0.58)b	21
OBA	0.84 (0.64–1.04)bc	38	0.91 (0.72–1.09)a	42
CEBA	0.62 (0.31–0.94)cd	28	No data	29
SLLP	0.92 (0.70–1.16)ab	57	0.66 (0.42–0.89)ab	35
CEAR	0.45 (0.26–0.65)d	21	0.49 (0.35–0.68)b	24
ER	0.37 (0.19–0.58)d	20	No data	No data
NEAR	0.54 (0.24–0.80)cd	32	No data	No data
Country	0.75 (0.64–0.85)	41	–	–

Table 5
Spatial and temporal variability in mean farmer (RD) yields across regions. Variabilities are expressed in absolute terms (standard deviations [SDs] between years across reporting districts within a region [temporal variability]; SDs between reporting districts within a region within years [spatial variability]); as well as in relative terms (SDs as a percentage of mean farmer (RD) regional yield).

Region	Farmer (reporting district) temporal yield variability (SD value [$t\,ha^{-1}$])	Relative temporal yield variability (SD as % of mean farmer yield)	Farmer (reporting district) spatial yield variability (SD value [$t\,ha^{-1}$])	Relative spatial yield variability (SD as % of mean farmer yield)
SEBA	2.01	131	2.40	157
SOBA	0.61	38	3.35	210
OBA	1.31	59	2.62	118
CBA	2.70	120	2.20	98
SLLP	1.68	105	2.57	160
CEAR	4.01	187	1.04	47
ER	3.40	200	2.07	113
NEAR	4.17	247	1.80	106

Comparative yield trials also showed considerable between-trial variability within each combination of year and region, as illustrated by Fig. 2. Within-trial variability was smaller than between-trial variability, and the mean contribution of the trial effect to total non-error variance of the yield trials far exceeded the contributions of hybrid and hybrid by trial interactions in all eight regions (Table 6). None of the 57 sets of cumulative relative frequency plots for other year-region combinations showed patterns which differed (by inspection) from those shown in Fig. 2 (data not shown). Although a review of those plots suggested (as seen in Fig. 2) that the range of yields within a single trial tended to increase with mean yield, analyses using coefficient of variation vs. mean trial yield failed to demonstrate that these effects were significant (data not shown).

4. Discussion

Opinions vary as to the suitability of data generated in CYTs as a basis to estimate potential, water-limited potential or attainable yields. Some authors (e.g. Spink et al., 2009; Berry and Spink, 2006) are comfortable in using data from trials of this kind to estimate genetic yield progress and estimating yield gaps in wheat and oil seed rape. Others (e.g., Cassman et al., 2003, 2010) consider that CYTs do not provide an adequate estimate of potential yield (and

Table 6
Means and SEs for relative contributions of the effects of trial, hybrid and trial by hybrid interactions to the total non-error variance in attainable (CYT) yields. Values in brackets in the "Region" column indicate number of years of data used to compute estimates of variance components.

Region	Mean relative contribution of the trial effect (%)	Mean relative contribution of the hybrid effect (%)	Mean relative contribution of the trial by hybrid effect (%)
SEBA (9)	94.0 ± 3.01	1.8 ± 0.57	4.2 ± 2.65
SOBA (7)	94.9 ± 1.44	0.4 ± 0.20	4.8 ± 1.39
OBA (7)	85.0 ± 2.05	5.1 ± 1.62	9.9 ± 2.60
CEBA (6)	86.1 ± 2.48	0.6 ± 0.36	13.3 ± 4.43
SLLP (7)	87.0 ± 5.37	2.8 ± 1.16	10.2 ± 5.68
CEAR (4)	87.4 ± 2.83	4.4 ± 2.62	8.3 ± 2.04
ER (6)	86.1 ± 5.51	6.7 ± 2.16	7.2 ± 3.04
NEAR (8)	88.6 ± 0.83	5.0 ± 1.05	6.4 ± 0.52

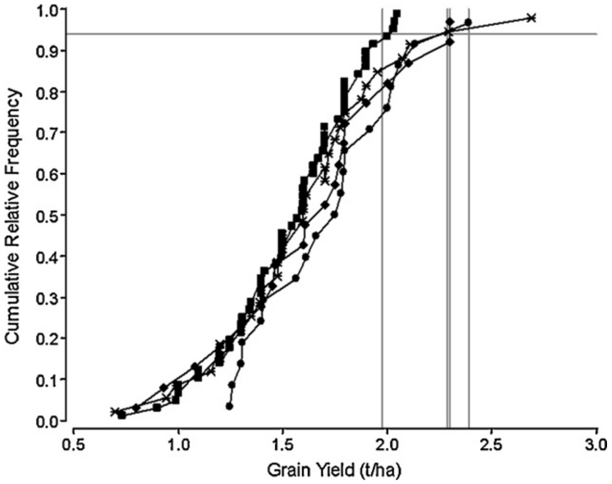

Fig. 4. Cumulative relative frequency distribution curves for reporting district by year combination values for four regions (solid squares: SEBA [7-y by 6 reporting districts], solid diamonds: SLLP [7-y by 3 reporting districts], crosses: SOBA [6-y by 5 reporting districts]), solid circles: NEAR [7-y by 3 reporting districts]. Each data point is a reporting district-by-year value, vertical lines mark the yield achieved at the 95% value (horizontal line) of the cumulative relative frequency distribution for each regional data set (i.e., the attainable (RD) yield estimator).

presumably, by extension, Yw and Yatt). There is also an impression among farmers that CYT results may be unrealistically high because breeders are assumed to apply more intensive management procedures that those typical of good farmers or because more productive fields are sought to locate the trials (de la Vega, pers. comm., Pozzi, pers. comm.). The contrasts between our estimates of Yatt based on CYTs and ICFs (Table 3 and Section 3.1) indicate that the former estimate is conservative and is unlikely to overestimate yield gaps. The contrasts between CYT- and RD-based estimates of Yatt (Table 3 and Fig. 4) indicate there is some risk of underestimation of Yatt if RD yields are used to estimate the Yatt. This finding bears on the conceptual foundation of the yield gap analyses used by Licker et al. (2010) and Gerber et al. (2010). For our data sets, the CYT data provided the most useful estimate of Yatt with the greatest geographical coverage. Importantly, the CYT database also allowed us to partition total variance into trial, hybrid and trial by hybrid components (Table 6). Estimates of Yatt derived from data generated in CYTs have been little used in yield gap analysis. Aggarwal et al. (2008) is a partial exception, but their report lacks statistical analyses of experiment-station (=breeder trial) variability across years and sites, and the temporal and spatial variability of Yatt and gaps (Tables 3 and 4 and Fig. 3) was not documented.

Significant (Table 3) and important, in both absolute and relative terms (Table 4 and Fig. 3), mean farmer (RD)/attainable (CYT) yield gaps were a feature of all eight sunflower producing regions of Argentina that have been distinguished in this study and were important at a consolidated country level. In three of the four regions that contribute most to the national harvest (Table 1), these gaps are close to 1 t ha^{-1}. Expressed as percentages of mean farmer yield, in six of the eight regions, yield gaps exceed the nominal 25% floor which has been suggested as the likely lower limit to yield gaps in commercial farming (Fischer et al., 2009). Three of the four regions contributing most to the national harvest have regional yield gaps in the 57–77% range. Taken together, these results are a strong argument to invest research efforts in determining the management (i.e., amenable to manipulation) constraints to yield that operate in the various regions.

The mean ICF/attainable (CYT) yield gap was significant for all five regions for which data was available (Table 3). For SEBA, SOBA

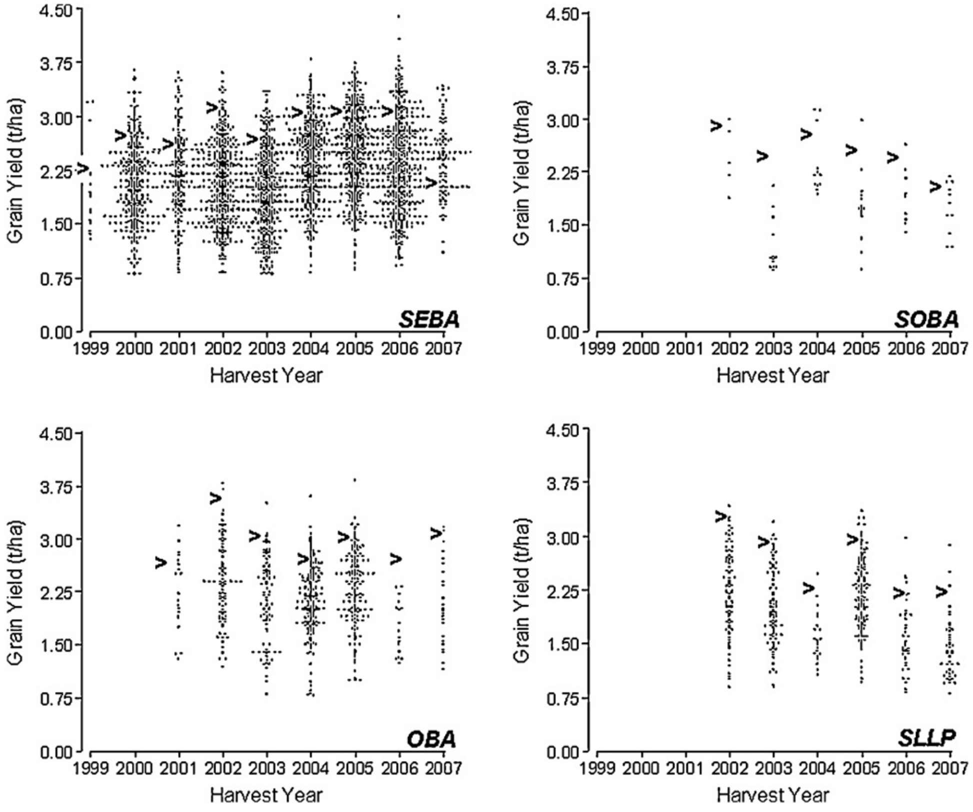

Fig. 5. Scattergrams showing distribution of individual field yields for several years in four regions. Each dot is a single data-point and dots are clustered around the vertical line for each year of record. Where data points overlap, they are spread laterally around the vertical for the appropriate year. Arrow heads next to each vertical series indicate the attainable (CYT) yield estimate for that year.

and SLLP, this gap was narrower than that for the corresponding mean farmer (RD)/attainable (CYT) metric for the region, suggesting that farmers who contributed to the individual field data base in these regions (but not in OBA or CEAR) outperformed the general population of farmers in their region. A majority of the individual field data points were for yields lower than that of the attainable (CYT) yield for the corresponding year-by-region combination (Fig. 5) but on average, and as pointed out in Section 3.4, slightly more than 10% of ICF values exceeded the attainable (CYT) estimate in the order of 9% of the latter value.

Although differences between regions were not significant for all metrics computed in these analyses, the overall picture indicates that significant inter-regional differences existed for farmer, attainable, individual field and Top10 yields (Table 3) as well as for mean farmer (RD)/attainable (CYT) and mean ICF/attainable (CYT) gaps (Table 4). These regional differences need to be studied in order to understand their origin. Their existence constitutes a justification of our use of regionalisation as an element of our approach to the study of yield gaps.

As is to be expected for rain-fed systems such as those of the sunflower producing regions of Argentina, attainable (CYT) yields were considerably less than those obtained in the most favourable trials for each year and region (Top10 yields, Fig. 3 and Table 3). Perhaps more surprising is the fact that the ULRY values (Fig. 2 and Table 3) tended to be rather similar across regions with the exception of the ER region. It is clear that neither the Top10 not the ULRY values, given their exceptionality, can be taken as useful reference points for yield gap analysis.

There is little data on potential (i.e., irrigated) sunflower yield in Argentina. The mean upper decile estimate obtained from CYTs conducted under irrigation ($\text{Top10}_{\text{irr}}$) at Ascasubi (slightly South of the SOBA region) over the period 1998–2008 was $5.1 \pm 0.17\,\text{t}\,\text{ha}^{-1}$, with an upper limit to irrigated yield of $5.9\,\text{t}\,\text{ha}^{-1}$. Funaro and Pérez Fernández (2005) and Funaro (pers. comm.), using a smaller number of hybrids over three years reported mean maximum yields for irrigated sunflower at Anguil (in the SLLP region) of $5.7 \pm 0.16\,\text{t}\,\text{ha}^{-1}$. These estimates of $\text{Top10}_{\text{irr}}$ and upper limit to irrigated yield are clearly greater than our rainfed ULRY values of 4.7 and $4.8\,\text{t}\,\text{ha}^{-1}$ for the SOBA and SLLP regions, respectively (Table 2). Although caution needs to be exercised in this context, our ULRY must be regarded as an underestimate of potential yield (in the sense of Fischer et al., 2009) across sunflower-growing regions of Argentina. Thus while in at least some years, very favourable environmental and biotic conditions are explored by sunflower crops in some locations in most regions of Argentina, even these crops appear to have experienced some limitations to yield.

Variability of yield estimates was an important feature of our analyses, whether at the RD level (Fig. 4 and Table 3), the CYT level (Fig. 2 and Table 6), or the ICF level (Fig. 5). Several important messages arise from this. At the reporting district level, the relative (to temporal) importance of the spatial dimension of this variability (Table 5) may mean that our regions were too broad and that effort should be invested in searching for regional divisions characterised by a lesser (in relation to temporal) variability. Equally, the temporal dimension of this variability should be explored in an effort to separate, if possible, management (i.e., potentially controllable) and climatic (seasonal water availability and other effects of weather) components. Analysis of the sources of non-error variance in the CYTs (Fig. 2 and Table 6) clearly shows that trial (i.e., location within region and year) was by far the most important component, far larger than the genotype and the genotype by trial effects. This result is consistent with the findings of Chapman and de la Vega (2002) for sunflower and Anderson (2010) for wheat. It is important to note that our results do *not* indicate that genotype is unimportant to growers when deciding the sourcing of their seed. In our analyses we compared yields obtained, in each year and region, using the most current hybrids produced by the various companies that compete in the Argentine market. de la Vega et al. (2007) and de la Vega and Chapman (2010) provide examples of the yield cost of sowing superseded hybrids that lack resistance to current strains of fungal diseases, as well as that of not taking advantage to the slow but steady increase in Yatt. Finally, the ICF data for the five regions for which this data was available emphasize a consistent (across years and regions) degree of variability in outcomes (Fig. 5). Yield variability at these three separate levels provides further support for the argument that it makes good sense to invest further research efforts into identifying the causes of this variability, which probably makes substantial contributions to the farmer/attainable yield gap.

The importance of within-region variability in all three databases used in this work has implications for attempts to determine yield gaps for rain-fed cropping systems using other methodologies. Where experiment station data are used to estimate attainable yield it would be important to ensure adequate spatial distribution and sampling intensity for these experiment-station estimates. Where models are used to estimate attainable rain-fed yields, an important proviso is the correct identification and weighting of the factors responsible for spatial variability so that results are truly representative of intra-regional conditions.

In drawing inferences from the results of our analyses, we acknowledge possible weaknesses. Perhaps the most important one is that we have used available (rather than obtained via planned sampling) data to construct the databases we have used. In some of our analyses (e.g., those performed on the CYT database) we have been able to use statistical techniques to mitigate bias and lack of balance between component trials. In others, such as the ICF data, this was not possible. The possible spatial imbalance between RD and CYTs is mitigated by the tendency of breeders to site a large proportion of their trials (but certainly not all their trials) within each region in the RDs that are regionally important in terms of sunflower production. In spite of these possible weaknesses, we believe that the magnitude and consistency of our main results is very strong and justifies the inferences we have drawn. A planned sampling exercise for this exploratory work would have been very complex and expensive. Now that our results have served to establish the importance of the existing yield gaps, future work will require a more careful geospatial positioning of individual fields and yield trials.

5. Conclusions

Our work has shown that significant and important farmer (RD)/attainable (CYT) yield gaps exist in all eight sunflower producing regions of Argentina; and that location-associated yield variability (apparently dominated by management and biophysical environmental effects) within regions and years was a feature of data incorporated into the RD, CYT, and ICF databases. These findings justify investing research efforts into identifying the causes of these yield gaps with the aim of narrowing them. Exceptionally high yields, as captured in the Top10 or ULRY metrics, are not useful reference values to be used in the context of yield gap analysis.

Role of the funding source

ASAGIR (Asociación Argentina de Girasol) funded data compilation and analysis, and authorised the publication of the results. AJH, CF, JI and MB designed the study, oversaw and/or performed the data analysis, interpreted the results and wrote the paper.

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