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Interannual variability of wheat yield in the Argentine Pampas during the 20th century

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Abstract

National long-term agricultural records offer an unique opportunity to improve our understanding of the patterns of variability of crop yield. In this paper, our objectives were: (i) to describe yield and yield stability of wheat crops (*Triticum aestivum* L.) and (ii) to identify some controls for their spatial and temporal variability. Their environmental controls (precipitation (PPT), photothermal coefficient and drainage type) were explored using a database covering the period between 1923 and 2000 and the main subregions of the Pampas.

Linear or bi-linear regression models were fitted to the relationship between yield and year for each of the 97 counties analyzed. Two traits derived from the temporal dynamics of wheat yield were used to characterize the spatial variability in yield trends: the inflection point (IP, the year at which the rate of increase in yield changed) and the difference between yield at the beginning and at the end of time-period considered (Δyield). Wheat variability trends were analyzed by plotting the absolute residuals and relative residuals of the regression models (absolute residual expressed as percentage of predicted yield) against year.

Forty counties displayed linear relationships between yield and time, while in the other 57 counties the relationship was bi-linear. On average, the IP occurred in 1970. Only a small portion of the overall variance in the IP, 11%, was explained by environmental variables (photothermal quotient (PTQ), as the ratio between mean monthly incident short-wave radiation and mean monthly temperature) suggesting that the modernization of agriculture was driven mainly by local factors (such as risk aversion or land tenure). The difference in yield between 1923 and 2000 was positively associated with the average precipitation during the crop cycle and the photothermal quotient between September and November. These variables accounted for 34% of the total spatial variability. Ninety-six counties showed higher yield variability at the end than at the beginning of last century. However, in 92 counties the increase in yield variability was lower than the increase in grain yield. This finding suggests that during the last century wheat production systems of the Pampas have been successful in increasing yield while maintaining or increasing relative yield stability. Absolute variability was associated with the photothermal quotient (13%), and precipitation (7%). The proportion of the spatial variance in the relative variability explained by the proportion of the county without drainage problems (DREN) was 31%, while PPT and PTQ explained 10 and 9%, respectively. Our results provide evidence against

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the trade-off between yield and yield stability, demonstrating empirically that simultaneous improvement of cultivars and management strategies may provide increases in both, yield and yield stability, in either low- or high-yielding environments.

Keywords: Wheat; Grain yield; Yield variability; Environmental controls; Argentina; Agricultural statistics

1. Introduction

Agricultural systems, for which data are available, provide an ideal system to study environmental and human effects on primary production. Analyses of national long-term yield records have been used to describe two important crop attributes: yield and, to a lesser extent, yield variability. During the 20th century global wheat (*Triticum aestivum* L.) yield increased considerably, from less than 1 to ca. 2.5 Mg ha^{-1}. This increase in yields was the most remarkable feature of the intensification of the wheat cropping system during last century. Two factors were largely responsible for the production levels achieved by farmers: better management practices (technological component of yield gains) and new improved genotypes (genetic component of yield gains) (Slafer and Kernich, 1996; Cassman, 1999).

The impact of crop management and its changes through time are difficult to assess because of its multi-dimensional nature. The components of the technological improvement are diverse (optimal sowing dates or densities, type and availability of machinery, amount of fertilizers and pesticides, irrigation, etc.) (Hall et al., 1992; Calderini and Slafer, 1999) and their importance varies spatially and temporally. The impact of technology depends on government policies and social conditions necessary to promote technological development and use (Cassman, 1999).

The contribution of genetic improvements on yield has been thoroughly analyzed in several cereals such as wheat (*T. aestivum* L.) (e.g. Austin et al., 1980), barley (*Hordeum vulgare*) (e.g. Riggs et al., 1981) oats (*Avena sativa*) (e.g. Wych and Stuthman, 1983) maize (*Zea mays* L.) (e.g. Duvick, 1984) and rice (*Orizya sativa* L.) (e.g. Ashraf et al., 1994). In general, the increase in yield of modern cultivars was mainly due to changes in the harvest index. A negative relationship between yield and yield stability was also reported, as modern cultivars were more responsive to environmental conditions than older cultivars (Calderini and Slafer, 1999). Despite the negative effects of genetic improvements on yield stability, it would be incorrect to expect more variable yields under cropping conditions. The net result of the opposing effects of management and genetic improvement will depend on how successful was the former to promote higher yields and to avoid the decrease in yield stability produced by the latter. Resource levels will also control these effects generating regional patterns of wheat yield.

Yield variability has received much less attention than yield trends (Slafer and Kernich, 1996). Calderini and Slafer (1998) showed that in 14 of the 21 counties analyzed in their study, wheat yield variability increased over the last century. However, this increase was relatively small compared to the increase in yield. Therefore, these authors suggested that wheat production systems have been, in general, highly successful in increasing yield without a concomitant increase in yield variability. However, analyzing data from counties or very large agricultural areas prevents the identification of particular environmental patterns responsible for, or associated with, the long-term trends in yield and yield stability.

Yield and yield variability (or its opposite: yield stability) of wheat crops in the Pampas region of Argentina were analyzed using long-term records at the county level. Our objective was to describe yield and yield stability of wheat crops and to identify some controls for their spatial and temporal variability. This study provides evidence to evaluate the existence of a trade off between yield and yield stability.

2. Methods

2.1. Study area

The Pampas of Argentina (located between 28 and 40°S and 68 and 57°W) covers approximately 34 million hectares (Mha) encompassing five Provinces (Buenos Aires and parts of the provinces of Entre

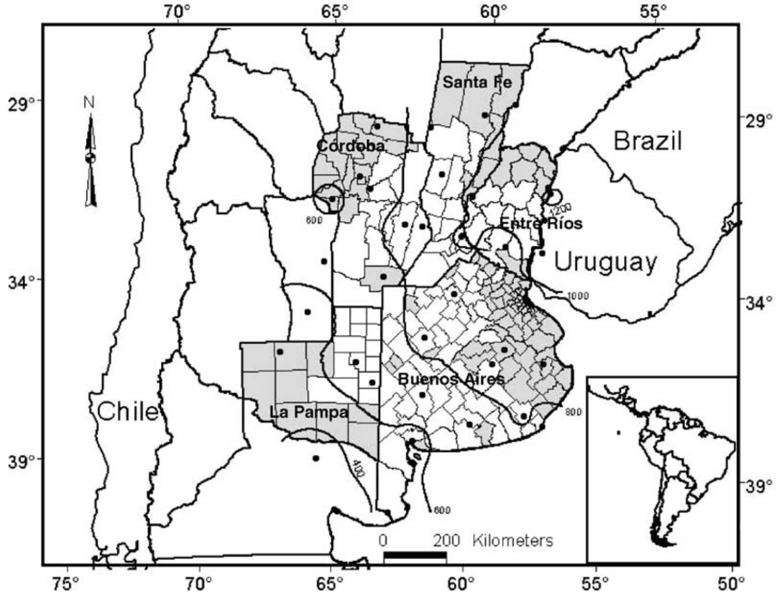

Fig. 1. Map of the study area and its location in South America. Each province (Buenos Aires, Cordoba, Santa Fe, La Pampa and Entre Rios) is subdivided into its counties. Gray colored counties had missing data and will appear white in the following maps. Dots correspond to the meteorological stations from which climatic variables were extrapolated. Isohiets (mm) are also depicted in the map.

Rios, Santa Fe, Cordoba and La Pampa) and ca. 250 counties (departments) (Fig. 1). The area includes five subregions of the Rio de la Plata grasslands, which extend over 70 Mha of Argentina, Brazil and Uruguay (Ghersa and Leon, 1999). Mean annual precipitation (PPT) ranges from 400 mm in the southwest to more than 1200 mm at the northeast. The rainfall regime tends to be monsoonal at the northwest and evenly distributed in the southeast (Hall et al., 1992). Mean annual temperature displays a north–south gradient of approximately 5 °C, from 13.5 to 18.5 °C. Mollisol is the dominant soil order over the area (SAGPyA, 1990) and Argiudols and Haplustols are the most representative soils of the region. However, the soils of large areas of some of the subregions of the Pampas (e.g. flooding Pampa) show important constraints for agriculture (alkalinity and salinity). In general, the soils, which developed from aeolian sediments, display a gradient in texture, being coarser at the southwest and finer at the northeast.

2.2. Wheat crops

During the last century important changes took place in wheat production on the Pampas. At the beginning of the 20th century, wheat crops occupied an area of ca. 4.5 Mha and yielded on average 0.65 Mg ha^{-1} per year. Wheat production was carried out mainly by immigrant farmers who rented the land for short periods (3–4 years) from landowners traditionally devoted to cattle and sheep rising (Barsky and Gelman, 2001). In these systems, productivity was low mainly because sowing and harvest were not mechanized and insecticides, fertilizers or herbicides were not used. By the end of the century wheat production was 4.5 times greater than in 1900, primarily because of a four-fold increase in yields (averaged 2.5 Mg ha^{-1} in 2000) and a rather modest (ca. 20%) growth of the sown area devoted to wheat (5.4 Mha) (SAGPyA, 2000).

At present, wheat crops are mostly grown as part of a 4-year agriculture/6-year pasture rotation with an increasing area of continuous agriculture (Satorre and Slafer, 1999). Tillage systems have changed radically from the conventional moldboard to less aggressive double disc seeders, reducing the number of tillages necessary. Direct-drill or no tillage systems have become more popular in recent years. By the end of the last decade ca. 1.7 Mha of wheat crops were direct-drilled (AAPRESID online report). Depending on the genetic material and location, wheat crops are sown from late May to early August and flowering takes place between late September and early November (Hall et al., 1992; Satorre and Slafer, 1999). Fertilization has not been common until recent years and the mean application rate during the 1980s was about 25–30 kg N ha^{-1} (Obschatko and del Bello, 1986). Pesticide use has been limited (Satorre and Slafer, 1999). This description applies for the average wheat cycle throughout the region, though differences certainly exist between sites.

2.3. Data selection

A database of wheat crop, climate and soil information was constructed. The spatial resolution of the database corresponds to the county level (department). Wheat crop information included wheat grain yield and harvested area. Data were digitalized from the archives of the Secretaría de Agricultura Ganadería Pesca y Alimentación (The National Secretary of Agriculture and Fishery, SAGPyA) for the period 1923–2000. Counties with less than 76 years of data or less than 10,000 ha of harvested area on average were not included in this study to avoid bias associated with missing values or local phenomena. Application of this criterion resulted in a total of 97 counties for subsequent analyses (ca. 60% of the area comprised by the five provinces). Most of the counties not considered were from the flooding Pampa subregion where soil constraints prevent commercial crops from being grown in large areas, and from the neighborhood of Buenos Aires, a metropolitan area with ca. 13 million people.

Climatic information was taken from FAO (1985). It consisted of mean monthly precipitation, temperature and radiation obtained from 38 stations located in, or close to, the area under study. Data points were interpolated to obtain spatial continuous values using Arc View GIS 3.2 Spatial Analyst Module. The inverse distance weighted (IDW) interpolation method, which assumes that each input point has a local influence that diminishes with distance, was used. Values assigned to each county corresponded to the average value of all the pixels that lay within its area.

Guerschman et al. (2003) database was used for soil information. These authors calculated the proportion of the country occupied by soils belonging to each of the seven classes of drainage defined in the Soil Atlas of Argentina (SAGPyA, 1990). This variable was selected because it synthesizes many edaphic characteristics of the soil, such as texture, profile depth and landscape position.

2.4. Analyses

An already published method for estimating yield gains and yield stability (Calderini and Slafer, 1999) based on previous studies (Finlay and Wilkinson, 1963; Eberhardt and Russell, 1966), was followed. Briefly, bi-linear regression models were fitted to the relationships between yield and year to characterize yield trends for the entire region and for each of the 97 counties. The residuals of this relationship were used to describe changes in yield stability. The following model was used:

$$Y_{\mathrm{w}} = (b_1 \times y + b_0) \times (y \leq b_3) + ((b_1 - b_2) \times b_3 + b_0 + b_2 \times y) \times (y > b_3) \quad (1)$$

where Y_{w} is wheat yield, y is the year after 1900 and b_0, b_1, b_2 and b_3 correspond to four parameters that describe the model shape: the intercept, the rate of grain yield increase during the first period, the rate of grain yield increment during the second period and the year at which the inflection point (IP) occurred, respectively. The terms $y \leq b_3$ and $y > b_3$ state conditions that, if true the term equals to 1 or 0 if false. The model requires initial values for the parameters b_0, b_1, b_2 and b_3 to start iterating until it finds the values that minimize the square of the difference between the observed and predicted values. To avoid biases associated with the initial values, broad ranges of values for each parameter were assigned. For each county, the PROC NLIN routine (SAS Institute, 1996) evaluated each of the possible combinations of starting values using the secant method (DUD, Ralston and Jennrich, 1978). The final criteria used to accept the bi-linear model was based on three premises: (i) there should be at least 10 years (points) between the inflection point and the beginning/end of the time-series considered; (ii) the slopes of each phase of the bilinear model should be significantly different; and (iii) the iteration should have converged to a set of parameters values that minimize the error sum of squares. Whenever one of these premises was not achieved, a linear

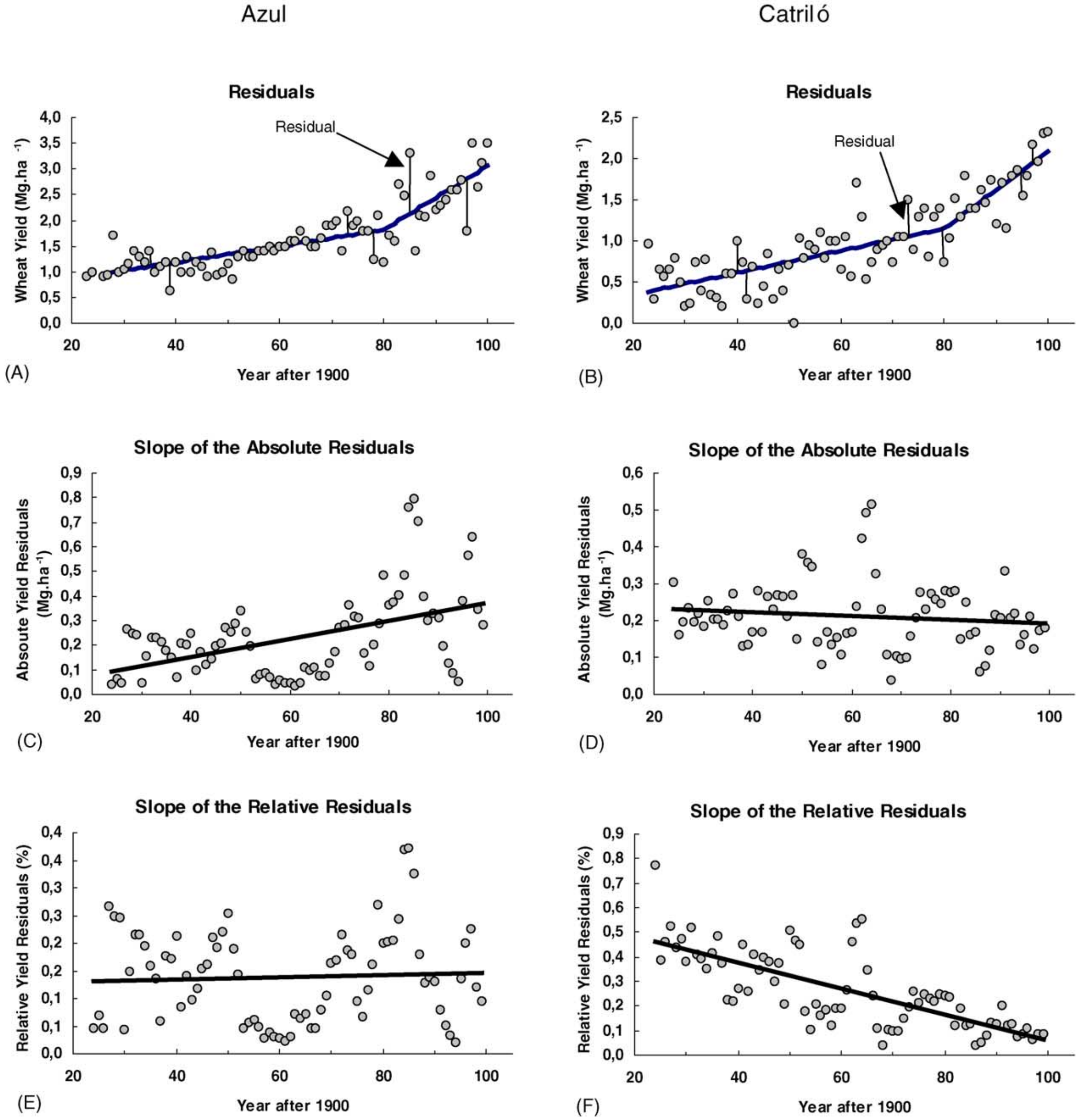

Fig. 2. Examples of the methodology used to obtain yield residuals and the absolute and relative residuals' slope for the counties of Azul, Buenos Aires province (left) and Catriló, La Pampa province (right). Parts (A) and (B): we fitted the bi-linear relationship between yield and year. The absolute residues of this relationship (the difference between the observed and predicted value) were our estimators of the absolute yield variability. Parts (C) and (D): the modules of the absolute residuals (averaged over three years periods—moving average) were plotted against year. The slope of this relationship (slope of the absolute residuals) was used to identify changes in wheat grain yield stability. Parts (E) and (F): the ratio of the absolute residuals and predicted yield was plotted against year to compare the magnitude of the changes in yield and yield variability.

model was fitted to the relationship between county yield and year. The difference between average yield of the last and the first decade of the period considered (Δyield; Δ(1991–2000); Δ(1923–1932)) and the year at which the rate of increase in wheat yield changed (IP) were used to characterize yield trends.

Fig. 2 shows, for two contrasting counties, the methodology followed to estimate yield variability trends. The absolute residuals were used to estimate variability independently from the impact of genetic and management improvement (Slafer and Kernich, 1996). Absolute residuals were computed as the difference between values observed and predicted by the model fitted,—Eq. (1)—(Fig. 2A and B). Negative absolute residuals were multiplied by -1 because we were only interested in absolute deviations from the mean. As average yield and yield gains differed between counties, the relative variability of wheat yield was also calculated. Relative variability was equal to the difference between actual and predicted yield values expressed as a percentage of the predicted value. In order to smooth the impact of abnormal years both types of residuals—absolute and relative—were averaged over 3-year periods (moving average). Finally straight-line regression models were fitted for the relationship between averaged absolute and average relative residuals and year. The slopes of these regressions were our estimates of wheat yield stability in absolute and relative terms (slope of the absolute residuals—SAR—and the slope of the relative residuals—SRR) (Fig. 2C and D, and E and F, respectively). A negative SAR indicates that yield variability decreased (the stability increase) with time, while a negative SRR, for cases with positive SAR, means that the increase in yield variability (numerator) was lower than the increase in yield (denominator).

Stepwise regression analysis (Kleinbaum and Kupper, 1978) was used to study the relationship between environmental variables and parameters related to yield trend and yield variability. Climatic and edaphic data were the independent variables, and the descriptors of yield trend and yield variability (IP, Δyield, SRR, and SAR) the dependent ones ($n = 94$ counties). For the specific case of the inflection point only counties whose yield trends fitted a bilinear model were considered ($n = 57$). To minimize the effect of the correlation between single environmental variables (temperature, precipitation and radiation), they were condensed into three variables: mean photothermal quotient (PTQ) between September and November (Fischer, 1985a; Savin and Slafer, 1991; Magrin et al., 1993), mean precipitation between July and December and the proportion of county's area occupied by well drained soils (DREN). PTQ was calculated as the ratio between mean monthly incident short-wave radiation and mean monthly temperature $-4.5\,^{\circ}$C (base temperature, Fischer, 1985a,b) for the period between September and November. PPT was equal to the sum of mean precipitation between July and December. DREN was the sum of the proportion of the county area occupied with soils belonging to the "well drained" and "moderately well drained" classes, as defined in the Soil Atlas of Argentina (SAGPyA, 1990). A multicollinearity analysis was also performed to detect correlations between independent variables using the SAS PROC REC routine (SAS Institute, 1996). For every regression model, the four variables presented a variance inflation factor (VIF) lower than 10. This value is considered a threshold above which the variances' increase in the parameter estimates are large enough to affect the predicted values.

3. Results

3.1. Yield trends

All the counties analyzed showed higher wheat yields at the end than at the beginning of the 20th century. The temporal dynamics of yield varied among counties. Forty counties, out of the 97 analyzed, displayed linear relationships between yield and time, while in the other 57 counties the relationship was bi-linear (Fig. 3). In general, the slope of the first portion of the period was lower than that of the second and, with the exception of three cases for the first slope, they were always positive. When each year yield was averaged for the entire region (i.e. regional scale) the slope of the first part of the period was 10.3 kg ha^{-1} per year, while at county level it ranged from -7.3 kg ha^{-1} per year (Pehuajo, Buenos Aires) to 27.0 kg ha^{-1} per year (Balcarce, Buenos Aires). The slope of the second part of the bilinear relationship was 34.5 kg ha^{-1} per year for the entire region, and varied between 25.3 kg ha^{-1} per year (San Justo,

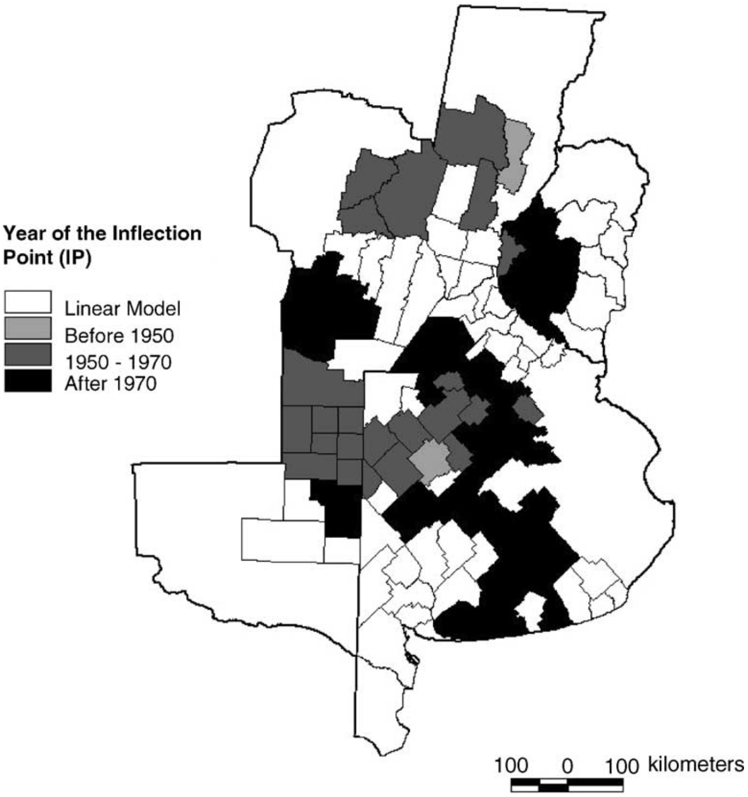

Fig. 3. Map showing the spatial variability in the year of the inflection point (IP) of the relationship between yield and year among counties.

Santa Fe) and 138.0 $\mathrm{kg\,ha^{-1}}$ per year (25 de Mayo, Buenos Aires) among counties.

The inflection point for the entire region occurred in 1970. At county level the IP exhibited a large variability, ranging from 1945 (San Justo, Sante Fe) to 1990 (Benito Juarez, Buenos Aires) (Fig. 3). The difference in yield between the first and the last decade considered (Δyield) spanned from 0.6 $\mathrm{Mg\,ha^{-1}}$ (Villarino, Buenos Aires) to almost 2.1 $\mathrm{Mg\,ha^{-1}}$ (Necochea, Buenos Aires). The area of lowest Δyield was found along a pheripherical band extending across northern Entre Rios, southeastern Cordoba, eastern La Pampa and southwestern of Buenos Aires (Fig. 4). The area of highest Δyield occurred along a northwest-southeast oriented axis between southern Santa Fe and southern Buenos Aires.

The results from the stepwise regression analysis showed that from the overall variance in Δyield, 34% was explained by climatic variables. The average precipitation during the crop cycle showed the highest association with Δyield (20%) while the average photothermal quotient between September and November accounted for the other 14% (Table 1). The inflection point was positively associated to the PTQ. However, this variable only explained 11% of the spatial variability in the IP.

3.2. Yield variability trends

At the regional level, the slope of the relationship between the absolute residuals and the year after 1900 (SAR) was positive ($P < 0.05$), indicating an increase in yield variability. At a more detailed spatial resolution, SAR was positive for 95 counties (approximately 94% of the area considered) and negative for the other 2 counties (Fig. 5). For 75 counties the slope of the absolute residuals was statistically higher than 0 ($P < 0.05$), while none showed a significantly negative slope ($P < 0.05$). The slope of the relative residuals (residuals expressed as percentage of predicted

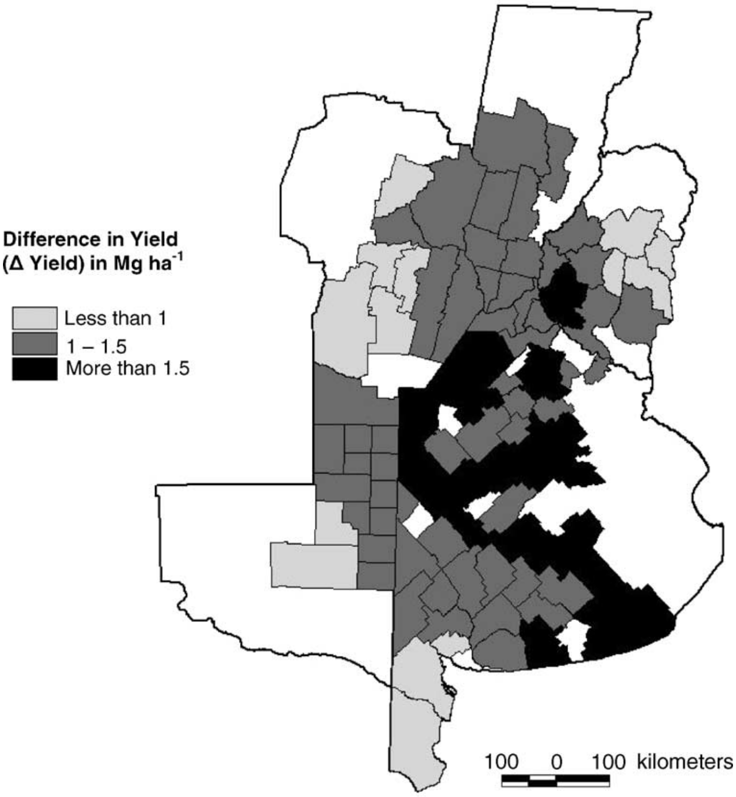

Fig. 4. Map showing the spatial variability in the difference in average yield (Δyield) between the last 10 years (1991–2000) and the first 10 years of the period considered (1923–1932). Values are expressed in Mg ha^{-1}.

Table 1
Relationships between the traits derived from the temporal dynamics of wheat yields to characterize yield and yield variability patterns and environmental variables

Dependent variable	Intercept	R^2	F	Independent variables	Regression coefficient	R^2 partial	P
Inflection point[a]	41.71	0.11	6.64	PTQ	18.68	0.11	<0.05
ΔYield[b]	−909.1	0.34	23.9	PPT	2.3	0.20	<0.001
				PTQ	842.44	0.14	<0.001
Slope absolute residuals (SAR)[b]	−6.32	0.20	11.46	PTQ	3.54	0.13	<0.001
				PPT	0.006	0.7	<0.001
Slope relative residuals (SRR)[b]	−0.01	0.50	27.65	DREN	0.001	0.31	<0.001
				PPT	0.00001	0.10	<0.001
				PTQ	0.0034	0.09	<0.001

Notes: The analysis were performed by stepwise multiple regression. Variables left in the model were significant at 0.15 level. Independent variables include the percentage of soils without drainage problems within a county (DREN), mean precipitation (PPT) occurred during wheat cycle (July–December) and mean photothermal quotient (PTQ) between September and November.

[a] $n = 57$.

[b] $n = 94$.

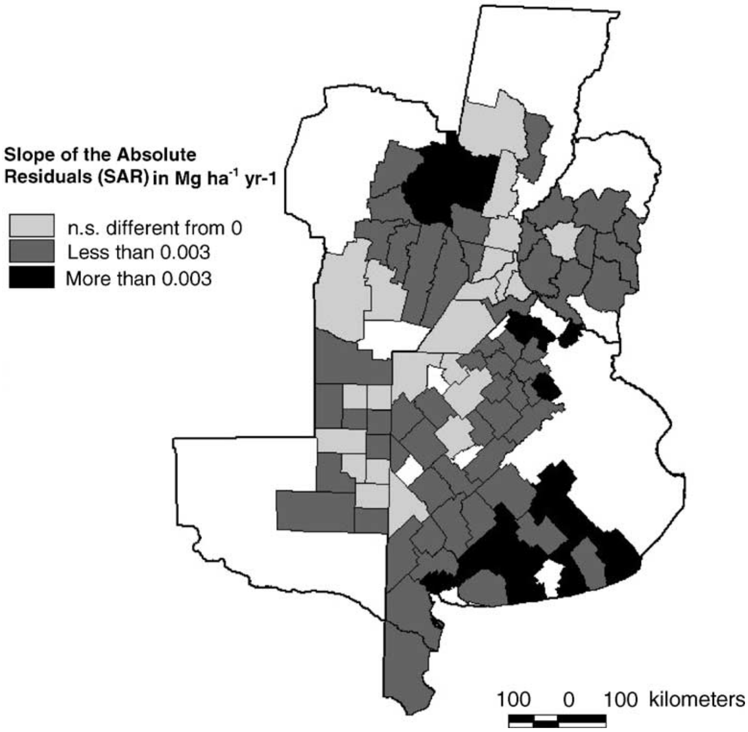

Fig. 5. Map of the region under study showing the spatial variability in the slope of the absolute residuals of the relationship between yield and year (SAR) expressed in $\mathrm{Mg\,ha^{-1}}$ per year.

yield) was either negative (52 counties) or not significantly different from 0 (45 counties), revealing that yield variability increased less than grain yield (Fig. 6). The slope of the absolute residuals was positively associated to the mean photothermal quotient for the period September–November and the mean precipitation during July–December (Table 1). PTQ explained 13% of SAR spatial variability while PPT accounted for 7%. Because PTQ and PPT were also correlated with Δyield, we regressed SAR to Δyield to check for spurious correlations. Although this relationship was significant ($P = 0.049$) its low coefficient of determination ($R^2 = 0.04$) suggests that the environmental variables selected by the model (PPT and PTQ) and Δyield must be explaining different aspects of SAR variability. The proportion of the spatial variability of the slope of the relative residuals explained was higher than for SAR, 50%. Almost two thirds of the explained variability (31%) were accounted for by the proportion of the county area occupied with soils without drainage problems (DREN). PPT and PTQ explained 10 and 9% of the variance, respectively (Table 1).

4. Discussion

4.1. Yield trends

The pattern of bi-linear increments in wheat yield between 1923 and 1997 found for the Pampas region is similar to the one reported for other wheat producing areas of the world (Calderini and Slafer, 1998; Slafer and Kernich, 1996). Slafer and Andrade (1989) discussed thoroughly the possible causes for the lack of increase in wheat yield during the first phase (e.g. wheat improvement programs' mainly aimed to increase grain protein content, frequently with a negative relationship to grain yield (Slafer et al., 1990)) and for the noteworthy increase in wheat grain yield during the second phase (e.g. the use of genetically

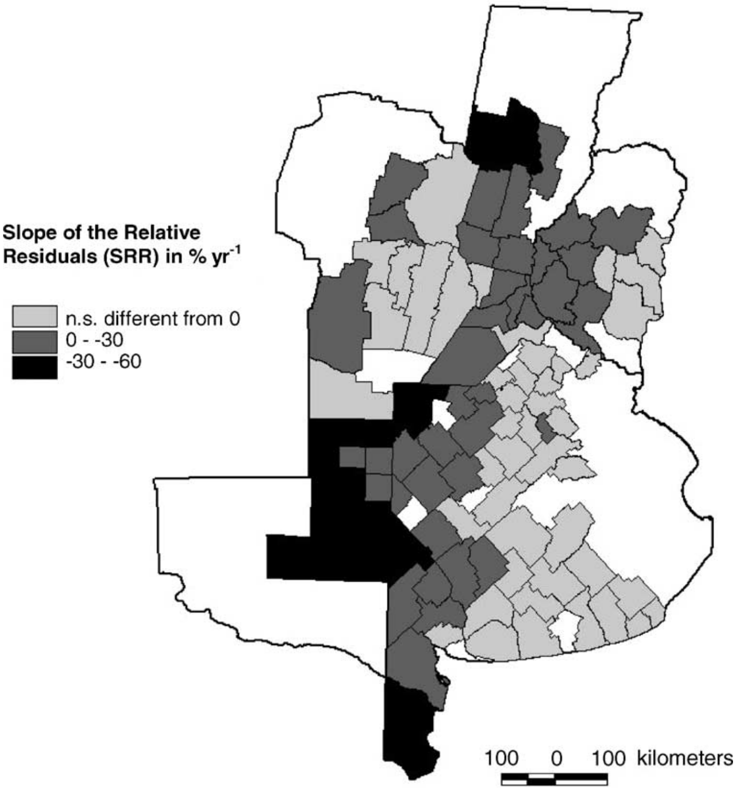

Fig. 6. Map of the region under study showing the spatial variability in the slope of the relative residuals of the relationship between yield and year (SRR) expressed in % per year. Slope values were multiplied by 10,000.

improved varieties (with semi-dwarfing genes), better agronomic practices, etc.).

The large variability found for the year of the inflection point at the county level may be an indication that the modernization of agriculture has been a local phenomenon, being more influenced by both socio-economic aspects (such as risk aversion or land tenure among others) than environmental variables. The low proportion of the spatial variance in the IP explained by environmental variables (11% by PTQ) supports this hypothesis.

The positive relationship found between precipitation and the photothermal quotient and the difference in yield (Δyield) agrees with the hypothesis that the impact of the agricultural intensification upon yield is higher at favorable than unfavorable environments (Slafer and Kernich, 1996; Cassman, 1999). This observation confirms for the first time at a county level what has been recognized from comparisons among whole counties (Araus et al., 2002). In the Pampas, water availability has been identified as one of the main climatic controls of crop yield (Satorre and Slafer, 1999). Under no water or nutrient limitations, Magrin et al. (1993) found a strong relationship between wheat yield and the photothermal quotient calculated for the 3 weeks prior to anthesis. The photothermal quotient reflects the opposing effects of radiation and temperature on grain number, and thus on wheat yield. Radiation increases spike weight at anthesis and hence kernel number while temperature decreases the duration of spike growth by speeding development rate, thus reducing spike weight and kernel number (Fischer, 1985a,b). The proportion of the explained Δyield variability rose to 79% when the average of the three highest yields of the county was used as an estimator of potential environmental quality (i.e. the degree of correspondence between wheat environmental requirements and the actual level of environmental factors).

4.2. Yield variability

The trends in wheat yield variability were different for the absolute and relative descriptors. In absolute terms yield variability increased as implied from the positive slope of the absolute residuals regressed against time while in relative terms yield variability decreased (negative slope of the relative residuals). This pattern was evident at the regional level as well as at the county level. The increase in absolute residuals would be expected if yield and yield variability were not totally independent. For example, if the error associated with the attainment (e.g. harvesting machine) or determination (i.e. weight) of yield had been a percentage of yield, the higher yields of the end of last century would appear more variable than those of the beginning. Relative residuals, by expressing yield variability as percentage of yield, avoid this limitation and provide a more suitable/adequate approach to understand the changes in yield variability (Francis and Kannenberg, 1978; Calderini and Slafer, 1998). The significant negative SRR found for the region, as well as for the majority of the counties, indicates that, even though both yield and yield variability increased during the 20th century, grain yield increment was higher than the increase in yield variability. Thus, the wheat cropping systems of the Pampas have been successful in increasing yields while maintaining or increasing yield stability.

These results differ from those reported by other authors. Hazell (1984) and Anderson et al. (1988) concluded that cereal yield gains were associated with an increase in yield variability. The methodology used by these authors may have been responsible for these differences. They restricted the analysis to the comparison between two specific periods of time. As pointed out by Calderini and Slafer (1998) this methodology presents two problems: it does not show trends and, more importantly, it confounds yield trends with yield variability changes. Moreover, the results from such a methodology are highly susceptible to the occurrence of an abnormal year.

Long-term weather changes may have played an important role in determining the observed pattern of yield variability. Our weather data (unpublished) and previous reports (Roberto et al., 1994; Viglizzo et al., 1995) showed a significant increase in rainfall in the driest part of the region during the last 75 years (La Pampa province, data not shown). Such changes may have important effects on yield and on yield stability. As precipitation variability is negatively related to mean annual precipitation (Lauenroth and Burke, 1995; Davidowitz, 2002), an increase in precipitation would not only have increased wheat yields but also would make them more stable; particularly in the subhumid areas where precipitation has increased markedly (Le Houérou, 1996). We also checked for a possible effect of changes in harvested area and the observed changes in yield variability. However, when the slope of the harvested area (the rate at which the harvested area changed per year) was regressed against SAR or SRR, the relationship was not significant ($P = 0.16$ for SAR and $P = 0.26$ for SRR).

The positive association between SAR and PTQ and PPT suggests that at favorable environments the increase in yield variability was higher than in sites where resources were less available. As counties with higher yield may have higher variability—simply because a site that yields, for example, $4\,\mathrm{Mg\,ha^{-1}}$ per year, may show a difference of up to $4\,\mathrm{Mg\,ha^{-1}}$ per year (if there is no yield) while a site with an average yield of $1\,\mathrm{Mg\,ha^{-1}}$ per year will only display a difference of $1\,\mathrm{Mg\,ha^{-1}}$ per year under the same situation—there is a possibility that this relationship may be due to statistical artifacts. However, the weak relationship between SAR and Δyield or average county yield suggests that this is not the case. Relative variability decreased less at favorable than at unfavorable environments meaning that, at marginal areas, the difference between the increase in yield and the increase in yield variability was higher than for areas best suited for wheat production. The pattern of response of both estimators of yield variability to environmental variables may be related to the relative contribution of genetic and technological contributions to grain yield gains in different environments.

4.3. Relative importance of genetic and technological contributions to yield gains

Previous studies have dealt with the difficult task of estimating the relative contribution of genetic and technological contributions to grain yield gains. In general, these studies have come to a convergent result: genetic and technological contributions were almost the same (Jensen, 1978; Silvey, 1979; Deckerd et al., 1985; Slafer and Andrade, 1991). Would this pattern be maintained for different environments? Should we expect that the relative importance of these two components of yield gains vary in space?

Genetic improvements and agronomic practices exert opposing effects over yield variability. Modern wheat cultivars are more responsive to improvements in environmental conditions than their older counterparts (e.g. Hucl and Baker, 1987; Ledent and Stoy, 1988; Cox et al., 1988). Calderini and Slafer (1999) confirmed this result in a study performed using data of cultivars released at different times in different environments. They found that the slope of the relationship between grain yield and an environmental index was higher in modern than in old cultivars and that modern cultivars out-yielded their older counterparts in virtually all conditions for counties with extremely different conditions. Thus, it is possible to expect a higher impact of genetic improvement on yield and absolute variability of yield on sites with adequate environmental conditions for wheat crops (those with high values of both photothermal quotient and precipitation). On the other hand, agronomic practices such as irrigation, fertilization, herbicides and pesticides use, date and rate of sowing, etc. not only improve yield by modifying the environment perceived by the crop but also make this environment less variable from year to year (Hazell, 1989; Tivy, 1989). For example, in wheat–rice double cropping systems in several Asian counties, differences in N supply in similar soils were identified as responsible for variations in rice yields of 3.6 Mg ha^{-1} when no N was applied (Cassman et al., 1998). Paruelo et al. (2001) found that, in the Central Plains of USA, irrigation not only increased crop production but also decoupled the system from the environmental factors that controlled its variability, making the system more stable. In addition, modern management practices aim to provide the required resources for crop growth and crop protection without deficiency or excess at each point in time and space.

The relative importance of the impact of genetic and agronomic improvement on wheat yield and on its temporal variability would differ spatially. The impact of genetic improvements would be highest at sites with good environmental conditions while the impact of better agronomic practices would be more important in less adequate sites for wheat production. Our results support this hypothesis. In the Argentine Pampas wheat grain yield of 97 counties increased during the 20th century. This increase in yield was related to a decrease in yield stability. However, in marginal areas of this study, the increase in yield was higher that the increase in yield variability while in the core areas the opposite tended to occur.

5. Conclusion

The mechanisms by which agroecosystems coped with the increasing demand on food and fiber in the past, now seem exhausted. Recent works have highlighted that grain yield increase through genetic improvement may be approaching its ceiling (Cassman, 1999). There is little possibility for expansion of agricultural lands due to the human demographic growth and actual availability of arable land for sustainable production. On the contrary, a reduction of the most fertile lands is the most likely scenario because of urbanization and land degradation. In this context, maintaining high and stable grain production is essential.

Our results showed that the impact of genetic and management improvement contributions on wheat grain yield and yield variability varied among sites. In low resource areas grain yield increased at a higher rate than yield variability. In contrast, in high resources areas the increase in yield variability tended to be higher (though not significantly) than the increase in grain yield. This finding highlights a “win–win” solution for the generalized idea of a trade off between grain yield and yield stability. To identify and to understand the underlying mechanisms responsible for this pattern constitutes an important prerequisite for the design of agricultural policies that may allow an adequate food supply as well as preserve our natural, social and economic capital.

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