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Analysis of wheat yield and climatic trends in Mexico

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Abstract

Wheat yields in Mexico, which represent an important measure of breeding and management progress in developing world wheat production, have increased by 25% over the past two decades. Using a combination of mechanistic and statistical models, we show that much of this increase can be attributed to climatic trends in Northwest states, in particular cooling of growing season nighttime temperatures. This finding suggests that short-term prospects for yield progress are smaller than suggested by recent yield increases, and that future gains will require an intensification of research and extension efforts aimed at raising wheat yields.

Keywords: CERES; Climate; Mexico; Wheat

1. Introduction

Wheat production in irrigated croplands provides a vital source of food and income for millions of people throughout the developing world. Over the next 50 years, yield increases in these systems will be needed to meet expected growth in food demand without significant rises in food prices and cropland area (Pingali and Heisey, 1999; Rosegrant et al., 2001). However, investments in public agricultural research critical to achieving the necessary yield gains have waned in recent years (Pardey and Beintema, 2001; Rosegrant et al., 2001). In addition, crop breeders are increasingly tasked with objectives other than high yields, such as improved grain quality and disease resistance (Peña, 1995). While these objectives are important, maintaining yield increases in farmers' fields remains a central goal of international wheat research.

Mexico is the home of the green revolution for wheat and one of the first countries to adopt new cultivars and technologies developed by the International Maize and Wheat Improvement Center (CIMMYT), in collaboration with the Mexican National

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Program. Wheat yield trends in Mexico thus represent an important indicator not only of progress within Mexico, but of present and likely future growth in other major developing world wheat systems. For this reason, several previous assessments of wheat breeding progress have focused on Mexico (Bell et al., 1995; Sayre et al., 1997; Rejesus et al., 1999). These studies considered yields up until 1990 and have generally concluded that the rate of yield progress in farmers' fields ''has been essentially constant for the last 30 years'' (Rejesus et al., 1999).

Wheat production experienced a rapid transition during the green revolution, a period of roughly 1960–1980 where widespread adoption of irrigation, new high-yielding varieties, and intensive use of fertilizers and pesticides led to a doubling of yields (Pingali and Heisey, 1999). In the post-green revolution period (since 1980), wheat yields in Mexico fluctuated about an average of 4 t ha^{-1} for much of the 1980s before rising roughly 25% to 5 t ha^{-1} by the end of the century (Fig. 1). Even with this yield gain, net imports of wheat more than tripled from roughly 800 Mt in 1980 to 2900 Mt in 2001, as domestic consumption rose and area planted declined (FAO, 2003).

What has caused the recent growth in wheat yields? State level records (SAGARPA, 2003) indicate that nearly all of the national yield increase since 1980 can be attributed to two factors: (1) yield gains in the Northwestern states of Sonora and Baja California, which contribute roughly 65% of national wheat production; and (2) decreases in area planted in the lower yielding regions outside of these states (Fig. 2).

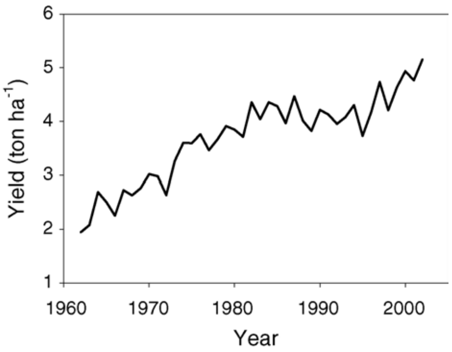

Fig. 1. Average wheat yields in Mexico, 1962–2002 (source: FAO, 2003).

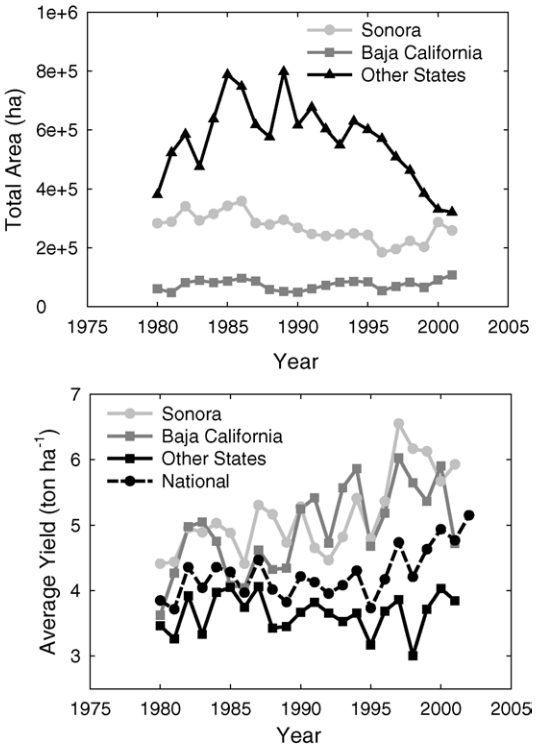

Fig. 2. Total harvested wheat area (top) and average wheat yields (bottom) in Sonora, Baja California, and all other states combined, 1980–2001 (source: SAGARPA, 2003). National wheat yields from Fig. 1 also shown for comparison.

Specifically, average national yield increased since 1980 by an average of 28.6 kg ha^{-1} $year^{-1}$, while states outside of Sonora and Baja California increased by only 1.1 kg ha^{-1} $year^{-1}$. Of interest here are the reasons behind the yield increases unique to the Northwest region. Potential explanatory factors include climatic changes, cultivar improvement, crop management practices (e.g., increased fertilizer use and better water management), and various major policy reforms (e.g., changes in land ownership, credit allocations, irrigation decentralization, and terms of trade) (Naylor et al., 2001). While not all of these changes were aimed specifically to increase yields, which, if any, of these factors have contributed to recent yield growth has important implications for future production.

Measurements at meteorological stations in this region reveal that growing season climatic conditions have not been stationary in recent decades (Fig. 3). An

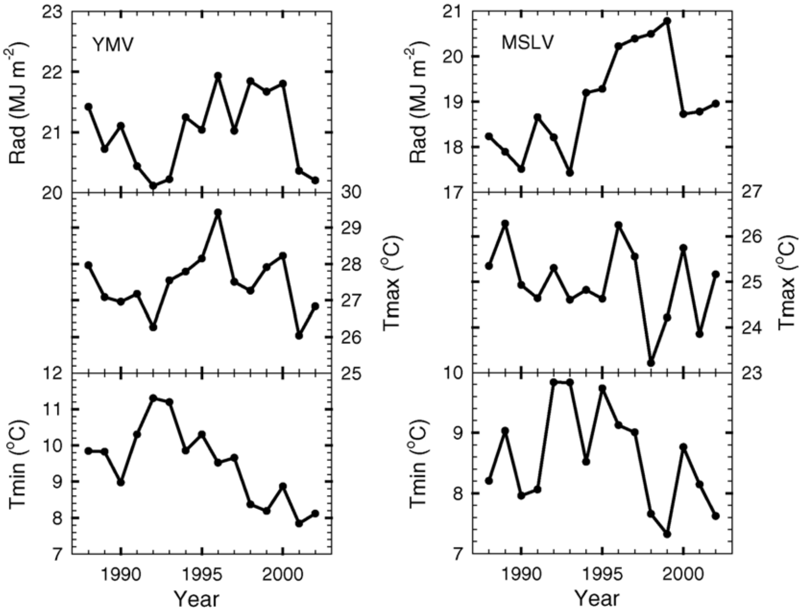

Fig. 3. Observed growing season (January–April) averages for minimum temperature (bottom), maximum temperature (middle) and solar radiation (top) for the Yaqui and Mayo valleys (left) and Mexicali and San Luis Rio Colorado valleys (right) of Northwest Mexico.

important step in the analysis of regional yield changes is therefore an assessment of the impacts of these climatic trends, as studies in several regions have shown that direct analysis of trends in harvest records can be misleading because climatic changes often confound the effects of management, technology and policy changes (e.g., Thompson, 1975; Bell and Fischer, 1994).

Efforts to correct for shifts in climatic changes have employed a variety of approaches, including time series analysis (Thompson, 1975; Nicholls, 1997), crop simulation modeling (Bell and Fischer, 1994; Andresen et al., 2001; Pathak et al., 2003) and spatial analysis of yield trends (Lobell and Asner, 2003a). Each of these approaches necessarily relies on assumptions that can induce substantial uncertainty in the results (Nicholls, 1998; Lobell and Asner, 2003b). In particular, empirical techniques suffer from limited sample sizes and potential bias to unmodeled variables, while simulation models are subject to a variety of model deficiencies, many of which are often poorly quantified. Thus, while assessment of climatic contributions to yield trends remains an important topic, interpretation of results using any individual technique is often imprecise. It is therefore our view that multiple different methods should be used whenever possible.

The goals of this study were to assess the impact of recent climatic changes on Mexican wheat yield trends and, by difference, to measure the true yield progress due to crop breeding and management changes. Both simulation and statistical modeling approaches were used to assess climatic impacts, given the uncertainties discussed above.

2. Materials and methods

We focused on the two major regions of wheat production in Mexico: the Yaqui and Mayo valleys in southern Sonora (YMV), and the Mexicali and San Luis Rio Colorado valleys along the border of northern Sonora and Baja California (MSLV). These areas accounted for 40 and 16%, respectively, of total national wheat production for the 2000–2001 growing season (SAGARPA, 2003). An additional 5% of production is derived from smaller regions located between YMV and MSLV in the state of Sonora.

The impact of recent climate changes on yield trends was assessed with two techniques. First, CERES-Wheat (Tsuji et al., 1994), a process-based crop growth model, was used to simulate yields for the last 15 harvest years (1988–2002) under constant management. CERES has been widely used to analyze crop response to climate variations and has been validated against observations in several studies (e.g., Ritchie and Otter, 1985; Lal et al., 1998; Rosenzweig and Tubiello, 1996). The effect of temperature on rates of several processes, including crop development, photosynthesis, transpiration, leaf growth, grain filling, and vernalization are modeled within CERES. However, the temperature dependencies of other processes are not directly modeled. For example, respiration rates are assumed to be proportional to photosynthesis and are therefore only indirectly influenced by climate.

As input to CERES, daily weather records for 1987–2002 were obtained for YMV from a local meteorological station operated by Centro de Investigaciones Agrícolas del Noroeste (CIANO), and for MSLV from a station operated by the Arizona Meteorological Network (AZMET; http://ag.arizona.edu/azmet/02.htm). Solar radiation was not measured at YMV pre-1998, and was therefore estimated from temperature extremes using the model of Bristow and Campbell (1984). The temperature-radiation model was calibrated using 1998–2002 data, which indicated successful simulation of radiation data ($R^2 = 0.76$).

Neither water nor nutrient stresses were simulated because these regions are irrigated and employ high fertilizer rates. Crop genetic coefficients for YMV, where the predominant cultivars are durum wheat varieties (*Triticum turgidum* L. var. durum) were defined based on the study of Bell and Fischer (1994). In MSLV, where bread wheat (*T. aestivum* L.) is more commonly grown, the following genetic coefficients were used: P1V = 0.5, P1D = 4.2, P5 = 2.0, G1 = 4.0, G2 = 2.0, G3 = 4.4, and PHINT = 75.0. These coefficients were derived using field measurements from an experimental field for the 1998–1999 cycle. Sensitivity analysis revealed that potential errors in these coefficients did not significantly change the results (see below).

To corroborate the CERES results, we performed an independent statistical analysis to determine the relationship between first differences (year-to-year changes) of yield and relevant climatic variables (Nicholls, 1997). In this case, we considered average minimum and maximum temperatures (T_{min} and T_{max}) and solar radiation (Rad) during January–April, the main months of wheat growth. A multiple linear regression was performed for each region, with the intercept of the regression representing the average yield change per year with climate held constant.

3. Results and discussion

Fig. 4 compares the recorded yields within each region to the simulated yields using CERES. The gap between simulated and observed yields reflects the difference between regional average yields and the potential yield when grown under stress-free and pest-free conditions, as simulated by CERES (Bell and Fischer, 1994). For instance, yields on local experimental stations in YMV with minimal stresses commonly surpass 8 t ha^{-1}, similar to the simulated values.

A high correlation between observed and simulated yield anomalies ($r = 0.87$ for YMV and 0.72 for MSLV) supports the use of CERES for simulating climate impacts in these regions. Moreover, repeated

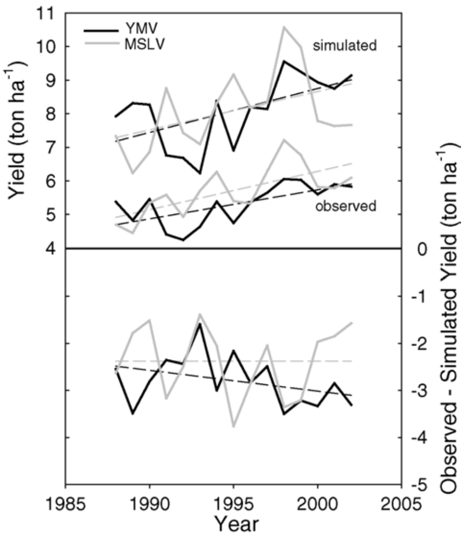

Fig. 4. Observed and CERES simulated wheat yields (top) in the Yaqui and Mayo Valleys (black lines), and the Mexicali and San Luis Rio Colorado Valleys (gray lines). Difference between observed and simulated yields (bottom).

simulations revealed that simulated yield trends were not very sensitive to the selected genetic coefficients. For example, the simulated yield trend (% change over study period) in MSLV was 22.0% using the coefficients above, but varied only between 20 and 23% for large ranges of genetic parameters ($0 < \text{P1 V} < 1$, $3 < \text{P1D} < 5$, $1 < \text{P5} < 3$, $3 < \text{G1} < 5$, $1 < \text{G2} < 3$, $65 < \text{PHINT} < 85$).

Observed yields increased by 86.6 ± 27.6 kg ha^{-1} year^{-1} in YMV and 114.1 ± 33.8 kg ha^{-1} year^{-1} in MSLV, which correspond to a 25.8 ± 8.2% and 32.5 ± 9.6% increase, respectively, over the 15 year period. The corresponding CERES-simulated changes in yield due to climatic trends were 25.5 ± 10.1% in YMV and 22.0 ± 12.4% in MSLV. Thus, according to CERES climatic trends can explain roughly 100% of the yield increase in YMV and 70% of the increase in MSLV over the past 15 years. A previous study of yields in the YMV region for 1968–1990 found that potential yields exhibited a linear decline over much of that time period associated with a small increase in temperature (Bell and Fischer, 1994). Thus, in YMV it appears that slight increases in temperature slowed yield progress in the 1970s, but that subsequent temperature declines since 1990 have promoted yield increases.

Table 1

Results of multivariate linear regression model between first differences of yield (kg ha^{-1}) and climatic conditions (1988–2002)

Region	Variable	Estimate	S.E.	*t*-value	*p*-value
YMV	Intercept	−11.4	92.1	−0.12	0.90
	$\Delta T_{\min}$	−456.2	143.5	−3.18	0.01
	$\Delta T_{\max}$	−63.6	135.9	−0.47	0.65
	ΔRad	203.4	225.3	0.90	0.39
Multiple R^2: 0.72, adjusted R^2: 0.63					
MSLV	Intercept	81.7	118.6	0.69	0.51
	$\Delta T_{\min}$	−443.1	168.9	−2.62	0.03
	$\Delta T_{\max}$	−158.2	111.4	−1.42	0.19
	ΔRad	−46.9	168.0	−0.28	0.79
Multiple R^2: 0.66, adjusted R^2: 0.56					

The regression analysis results for wheat and growing season climate conditions are shown in Table 1. The intercept of the regression represents the average yield change with climate held constant. For YMV, the average climate-adjusted yield change was −11.4 ± 92.1 kg ha^{-1} year^{-1} (−3.4 ± 27.5% for the 15-year period) while for MSLV, the adjusted yield change was 81.7 ± 118.6 (23.3 ± 33.8%). The substantial uncertainties associated with the regression estimates demonstrate the inherent difficulty in statistically separating climatic signals in yield trends (Gifford et al., 1998; Godden et al., 1998; Nicholls,

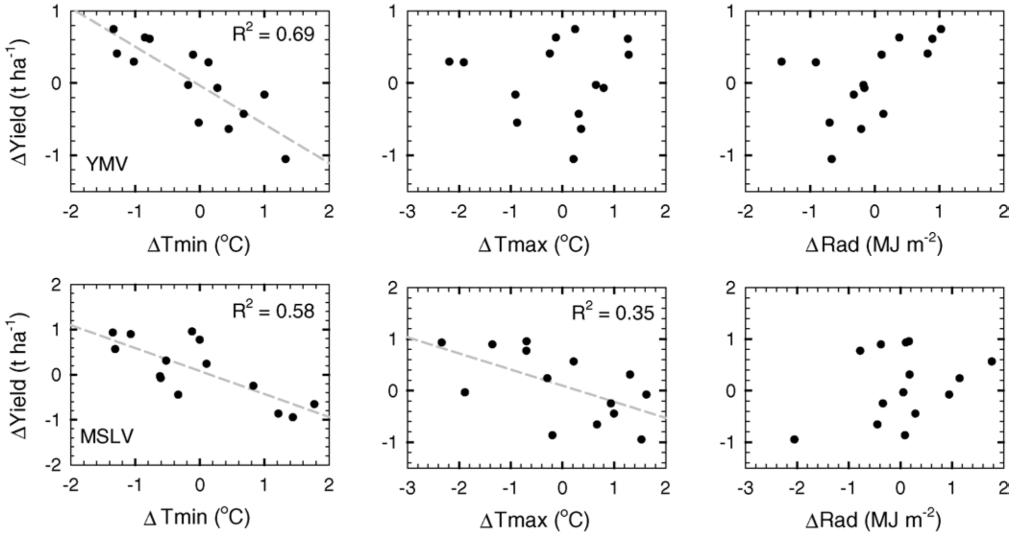

Fig. 5. Scatter plots of change in wheat yield vs. change in growing season average minimum temperature (left), maximum temperature (middle), and solar radiation (right) for the Yaqui and Mayo valleys (top), and the Mexicali and San Luis Rio Colorado valleys (bottom). Best-fit regression line and R^2 are shown for variables with significant correlations with yield changes ($p < 0.05$).

Table 2
Observed trends in growing season climatic conditions and their estimated impact on yields (1988–2002). Observed yield trends were 86.6 kg ha^{-1} $year^{-1}$ for YMV and 114.1 kg ha^{-1} $year^{-1}$ for MSLV

Region	ΔT_{min} (°C $year^{-1}$)	Estimated yield impact (kg ha^{-1} $year^{-1}$)	ΔT_{max} (°C $year^{-1}$)	Estimated yield impact (kg ha^{-1} $year^{-1}$)	ΔRad (MJ m^{-2} $year^{-1}$)	Estimated yield impact (kg ha^{-1} $year^{-1}$)
YMV	−0.161	73.5 ± 23.1	−0.001	0.1 ± 0.2	0.019	3.8 ± 4.2
MSLV	−0.057	25.2 ± 9.6	−0.059	9.3 ± 6.5	0.138	−6.5 ± 0.1

1998; Lobell and Asner, 2003b), resulting from a combination of limited sample sizes and imperfect correlations between yields and growing season average climatic conditions. Nonetheless, the result that yield trends are significantly lower when holding climate constant corroborates the conclusions from the CERES analysis above.

The results in Table 1 also reveal significant negative yield responses to higher nighttime temperatures (roughly 10% reduction of yield for $\partial T_{min} = 1$ °C), with a much smaller and statistically insignificant effect of daytime temperature and solar radiation ($p > 0.10$). The relationships between the individual climatic variables and yield changes are shown in Fig. 5, further illustrating the singular importance of nighttime temperatures in both YMV and MSLV. This finding is similar to that of Peng et al. (2004), who showed a negative response of rice yields to increased minimum but not maximum temperature. The physiological mechanisms associated with this response are not clear, although they likely involve greater rates of plant respiration during warmer nights (Stone, 2001).

The individual impacts of each climatic variable on yields trend were assessed by multiplying the trend in that variable by the yield response computed in Table 1. The results, shown in Table 2, emphasize the significant positive impact of recent decreases in T_{min} in YMV, which alone could explain 85 ± 27% of the yield increase. In MSLV, nighttime temperatures have also cooled slightly, although the predicted benefit to yield was only 22 ± 8% of the observed trend.

4. Conclusions

We conclude that increased yields of Mexican wheat since 1980 can be largely attributed to improved climatic conditions, and therefore that net gains from cultivar improvement and management changes have likely been smaller than assumed in previous studies that found no evidence for slowing of yield gains in the post-green revolution period (e.g., Rejesus et al., 1999). It may be that some changes have had a positive impact on yields, only to be cancelled out by other policy or management changes. Here we were only able to isolate the net effect of all non-climatic factors.

Given the recent emphasis in CIMMYT on breeding objectives other than increased yields, and the well-documented difficulty of simultaneously breeding for these objectives and higher yield potential (Peña, 1995), these results alone cannot be used to assess the return from recent research investments. For example, previous studies have shown substantial gains to farmers in these regions from maintenance breeding efforts such as rust and karnal blunt resistance, which prevent losses in productivity and reduce management costs (Bell et al., 1995). However, the evidence for a yield plateau since 1980 does suggest that achieving future yield increases in irrigated wheat systems will require significant breakthroughs in wheat yield research and management.

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