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Sixty years of irrigated wheat yield increase in the Yaqui Valley of Mexico: Past drivers, prospects and sustainability

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ABSTRACT

Continued global wheat yield increase (about 1.3% p.a. for 2000–2019) remains an essential condition for greater world food security. Relevant to this challenge is the rise in average farm yield (FY) of irrigated spring wheat in the Yaqui Valley of northwest Mexico from 2 to 7 t/ha between 1960 and 2019. Since the early 1950s the region has been the prime target of wheat research by the International Maize and Wheat Improvement Centre (CIMMYT) and its predecessors, research still having significant impact on wheat in the developing world, a grouping that today delivers more than half the world's wheat. FY increase was investigated in detail by dividing the interval into three 20-year periods, correcting FY for the strong influence of inter-annual variation in January to March minimum temperature (Tmin J-M, warming lowering yield around 7%/°C) and measuring the remaining linear increase in FY (Fischer et al., 2022). Total yield increase, corrected for Tmin J-M and CO_2 rise, relative to average yield in each period, was 4.17%, 0.47%, and 1.59% p.a. for 1960–79, 1980–99, and 2000–19, respectively. The breeding component, estimated by the increase in the Varietal Yield Index in farmers' fields, rose at 0.97%, 0.49%, and 0.71% p.a., respectively. The remaining yield change (3.16, −0.02% and 0.87% p.a., respectively) comprised the net effect of improved crop management (agronomic progress) plus that of off-farm changes, together here called agronomy+ . Major changes in agronomy included: a large increase in fertiliser N use, benefitting early on from a large positive variety × N interaction; in the second period a switch to planting on raised beds and a decline in rotational diversity; and in the final period, consolidation of operational crop units and probably more skilful and timely management. Off-farm developments saw strong government financial support in the first period, but in the second period breakdown of the traditional small holder land system and withdrawal of government support. The last period saw better prices and improved access to technical advice. Breeding progress is expected to continue in the Yaqui Valley but at a slowly diminishing rate (currently 0.66% p.a.), while progress from new agronomy appears limited. Although FY gaps are small, some gap closing remains possible, and 1.2% p.a. FY progress is estimated for the next 20 years in the absence of new technologies. World wheat food security without area increase will increasingly depend on developing countries where yield gaps are generally wider and gap closing prospects better. Biophysical sustainability of the Yaqui Valley wheat system is moderately good but N management and diversity can be improved.

1. Introduction

World wheat yield increase over the last 60 years has been invaluable for food security (Fig. 1a), holding world wheat area steady and real wheat prices at reasonable levels. Wheat yield in the Yaqui Valley of Mexico, with around 140,000 ha of irrigated wheat each year, is an important part of this picture. Yield in the Valley increased about 250% over the 60 years 1960–2019 (harvest years), from 2 to 7 t/ha (Fig. 1a). Similar relative increases in wheat yield have been seen in many developing countries (Fischer et al., 2014), partly because of spreading of the technologies first developed in the Valley by the International Maize and Wheat Improvement Center (CIMMYT) and Government of Mexico colleagues, such that over 50% of the world's wheat now comes from the developing world (FAOSTAT, 2017–19 data for Asia, Africa and South America, accessed 25 Nov 2021, fao.org/faostat/en/#data). Thus, there are important lessons for the world in the Yaqui Valley wheat yield progress especially because about 60% of developing world wheat production is under irrigation (Fischer et al., 2014) and technologies for irrigated wheat have large positive spill-over effects in favourable rainfed conditions.

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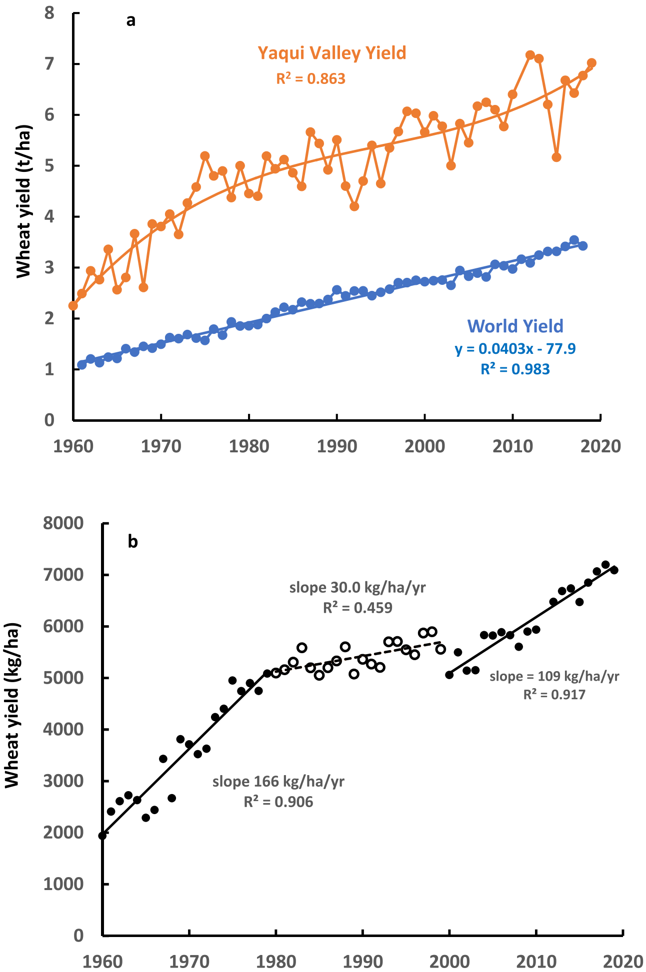

Fig. 1. (a) Average wheat yield (t/ha) for the world and for the Yaqui Valley of Mexico from 1960 to 2019. (b) Yaqui Valley wheat yield (kg/ha) broken into three successive 20-year periods spanning 1960–2019 with yields adjusted to a common average minimum temperature from January to March of 8.3 °C. Sources: FAOSTAT (updated to Oct 2021) and Fischer et al. (2022) for more details; Yaqui Valley yield in 1977 adjusted up 750 kg/ha for leaf rust losses, 2011 dropped because of frost damage.

An earlier paper (Fischer et al., 2022) explored the influence of weather on the change in wheat yield (hereafter called farm yield, FY) in the Valley over the 60-year period, as well as uncovering the overall effect of technology and other factors. Analysing the three successive 20-year[1] sub-periods comprising the 60 years permitted removal from FY change of the effects of weather (principally captured in the negative response of FY to average January to March minimum air temperature (Tmin J-M)), these months covering the period of tillering to early grain fill for wheat planted as recommended. After this correction, three quite different lineal rates of FY increase were revealed:

- 1960–1979 166 ± 15.3 kg/ha/yr, or 4.49 ± 0.41% p.a. (relative to period mean FY)
- 1980–1999 30.0 ± 8.1 kg/ha/yr, or 0.59 ± 0.16% p.a.
- 2000–2019 109 ± 9.7 kg/ha/yr, or 1.77 ± 0.16% p.a.

These results are summarized in Fig. 1b showing FY corrected for changes in weather (annual Tmin J-M) across the three 20-year periods by adjusting annual FY to the 60-year average Tmin J-M (8.30 °C) according to Tmin J-M sensitivities found in Fischer et al. (2022). This accounted for year-to-year fluctuations and for any Tmin trend across the whole period which amounted to an increase of Tmin J-M of 1.0 °C. The original a priori division of the period into three equal successive 20-year subperiods thus captured two major changes in the rate of yield increase (and an irregularity between 1999 and 2000 which will be discussed later). The term "new technologies" is used here, but it should be noted this includes not only the expected effects of new varieties (breeding) and new crop management (called crop agronomy hereafter), expected to be generally positive, but also other effects, either positive or negative, of any changes in socioeconomic factors along with ones in the natural resource base of cropping (Fischer, 2016). Since the breeding component is easier to estimate, the effect of agronomy and other factors, together termed agronomy+ , is calculated by removing breeding progress from total progress.

There have been various studies to separate the breeding and agronomy components of yield progress. A recent example is Rizzo et al. (2022) who subtracted from the weather-corrected upward yield trend in irrigated maize yield in Nebraska the agronomic contribution estimated from detailed input data, to come up with a surprisingly low contribution from breeding. For wheat the subject was thoroughly reviewed in Bell et al. (1995), arriving at an average contribution of breeding around 40% from four cited estimates. Probably the most appropriate methodology for measuring this contribution in a region where varieties grown are recorded, popularized by Silvey (1981) in the UK, was the calculation of an annual Variety Yield Index (VYI, see later). This permits a reasonably accurate measure of the impact of new varieties on yield increase in farmers' fields. Bell et al. (1995) went on to apply the technique to wheat in the Yaqui Valley for the period 1968–1990. They estimated that breeding progress contributed 28% of the weather-adjusted FY progress. Many studies have also tried to separate the various components of improved crop agronomy but this always proves difficult because of lack of data and factor collinearity. Bell et al. (1995) concluded that increased N fertilisation contributed 48% of the FY progress in their Yaqui Valley study and other agronomic factors the remainder; positive variety by agronomy interaction (e.g., variety × N) can also contribute to progress but was not considered important for 1968 versus 1990 N levels.

Economists tend to measure progress and sustainability in terms of the increase in total factor productivity, a good example for wheat in environments like the Yaqui Valley is the dissection of such productivity growth by Rejesus et al. (1999). Crop scientists have adopted a complementary area-based approach, which will be followed here. Thus, focus is more on change in yield and in all relevant individual yield-enhancing and limiting factors where data is available. The analysis was taken back to 1960 to cover the whole period of the Green Revolution as well as subsequent events up to 2019, for wheat over this period is a unique example of substantial cropping intensification. The last 20-year period studied is especially important for setting current R and D investment strategies and projecting progress, at least into the near future. Finally, the biophysical sustainability, including impacts on the surrounding environment, of the now intensive wheat cropping in the Yaqui Valley has become topical, and is discussed briefly.

2. Methods

The Yaqui Valley irrigation area (Cajeme Irrigation District)[2] extends between latitude 27–28° N along the coastal plain of Sonora, Mexico, lying to the southwest of the Sierra Madre Occidental mountains, in which the principal portion of the Yaqui River basin is located (Fig. 2). Median annual runoff is 2700 GL and up to approximately 6000 GL of

[1] The so-called 20-year periods (e.g., 1960–1979) comprised 19 year each, in order that analyses of each period were entirely independent. Years refer to year of harvest.

[2] Throughout this refers to the Distrito de Desarrollo Rural 148 and includes DDR 041 and DDR 018

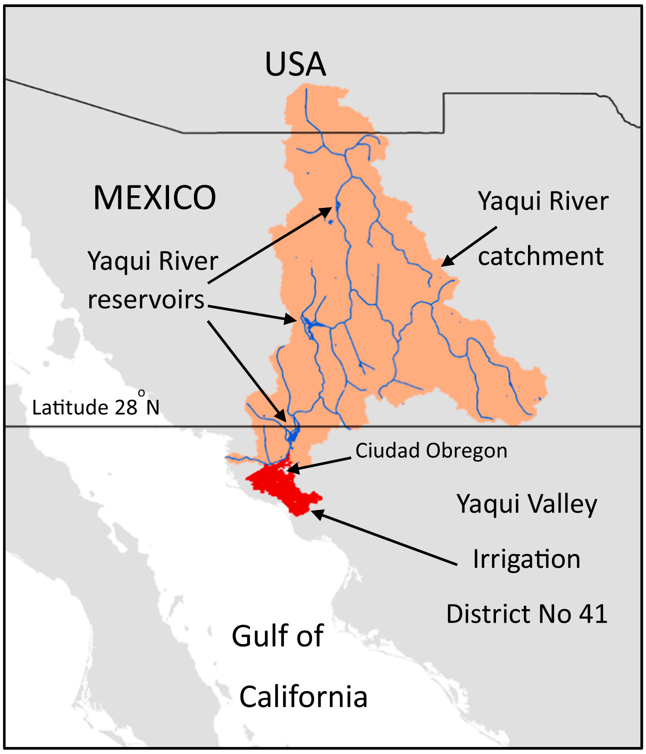

Fig. 2. Map showing the location of the Yaqui Valley Irrigation District and the Yaqui River catchment supplying the Valley with irrigation water (map courtesy Kai Sonder, CIMMYT).

water storage is available across 3 reservoirs, with a maximum of 233,000 ha developed for irrigation by 1963 (Dean, 2012). Water is supplied by an extensive canal system, and some ground water pumping, while deep open drains take excess water and salt to the Gulf of California (Schoups et al., 2012). Rainfall is bimodal with greater catchment runoff in winter, but greater rainfall in the irrigated area in summer. Yaqui Valley rainfall averages around 300 mm, but only 60 mm in the winter-early spring when wheat is grown (for complete weather details see Fischer et al., 2022). At the outset, land ownership was mostly small holder (< about 20 ha), initially about 60% (of land area) private and 40% with *ejidatarios*[3]; after land reform and expropriation in 1975 this shifted to 55% *ejidatarios* (Matson, 2012), followed by further changes described later. Agricultural research began in the Valley in the late 1940 s and continued largely with farmer and Rockefeller Foundation support until the Government of Mexico set up the Centro de Investigaciones Agricolas del Noroeste (CIANO) in the 1955 and CIMMYT was formalized in 1966. Wheat, a cool season or winter-spring crop, either bread wheat (BW, *Triticum aestivum*) or durum wheat (DW, *Triticum durum*) has always been the main crop in the Valley. Wheat-soybean (*Glycine max*) was a common double cropping system, at least initially when water was available; otherwise, wheat followed cotton (*Gossypium sps*) or more commonly summer fallow. Crops competing with wheat in the winter cycle included cotton, cool season maize (*Zea mays*), safflower (*Cathamos tinctoris*) and vegetables, but in total they never exceed the wheat area. The first semidwarf wheat varieties were released in 1962, followed by their rapid and complete adoption in less than 3 years. Over the study period (1960–2019) change has continued in varieties, agronomic practices, and policies (key events chronologically listed in Supplementary Table 1).

2.1. Overall approach to technological change in yield

While technological progress was quite linear after correction for Tmin J-M changes, especially in periods 1 and 3 (Fig. 1b), the factors influencing progress are unlikely to be exactly linear with respect to time; this was especially evident in genetic improvement (see Fig. 3b). Therefore, a simpler procedure than linear regression was used to disaggregate progress while maintaining the Tmin correction identified by linear regression in Fischer et al. (2022). This involved calculating the difference between the average temperature-corrected FY for the first and last three years of each 20-year period and expressing this relative to the whole period average yield (again temperature corrected) and dividing by 17 for the effective temperature-corrected per annum (% p.a.) yield increase. The above simple procedure was used to calculate the annual effect on FY of the steady increase in CO_2 as measured at Mauna Loa observatory in Hawaii (rising from 317 ppm in 1960 to 413 ppm in 2019). An FY elasticity with respect to CO_2 of 0.4 was assumed (Tubiello et al., 2007); in other words, the overall 27% CO_2 (relative to the average, 357 ppm) would have delivered an FY increase of 10.8%. Allowing for this CO_2 increase converted the

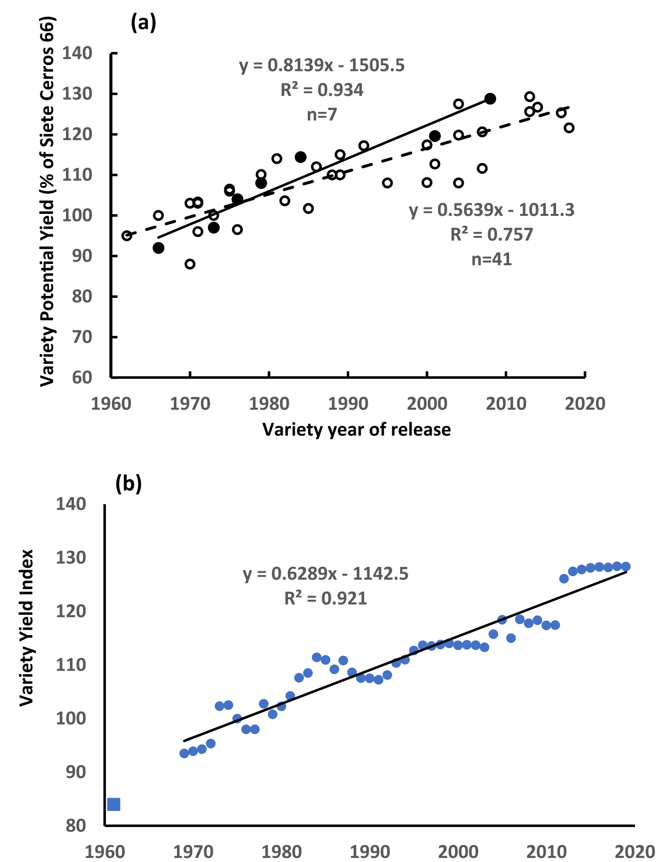

Fig. 3. (a) Potential yield (PY as % of Siete Cerros 66) of 41 varieties released in the Yaqui Valley 1961–2019 and each tested in vintage trials over several years between 1970 and 2017. The seven key varieties grown by farmers are shown with solid symbols and an unbroken line. (b) Time change in the Variety Yield Index (again relative to Siete Cerros 66 set at 100) for the Yaqui Valley for 1961 (square symbol) and from 1969 to 2019 (see text).

[3] *Ejidatarios* are small holders in the Mexican *ejido* system of communal land access and management which was set up in the 1930 s. Ownership of the land remained with the Mexican Government, as largely did the supply of credit, inputs and technologies.

temperature-corrected increase into a lower rate of progress,[4] called here climate-corrected yield progress.

2.2. Breeding progress

Breeding progress employed the Variety Yield Index (VYI) of Silvey (1981) for calculating variety progress in farmers' fields, as used earlier by Bell et al. (1995). It is based on (1) the area of varieties grown in any year, and (2) potential yield (PY) of these varieties. Dealing firstly with PY, it was measured in vintage (or era) trials conducted by various researchers at CIANO (later renamed CENEB) over the period 1970–2018. The station is near the centre of the Valley on a representative soil type and variety interactions with soil type are seen to be small in off-station variety comparisons. In the vintage trials, older and more recent varieties were compared side-by-side under potential conditions, meaning irrigation and high fertility, and including disease, weed, and lodging control if necessary, as elaborated in Fischer (2016). Special attention was made to avoid bias which might arise from disease in older varieties and from edge effects, interplot competition and wide interrow gaps. PY values were expressed relative to the variety Siete Cerros 66, a broadly adapted high performing semi-dwarf bread wheat, present in all the vintage trials. Thus, varieties were compared to Siete Cerros 66 during at least 5 years for recent ones to over 25 years for older varieties. The variety Siete Cerros 66 averaged between 6 and 8 t/ha in these vintage trials (mean 7.06 t/ha over 31 years) and showed no time trend. Trial agronomy was the best at the time so that positive interactions between variety and agronomy were included in the PY estimate; however such interactions were small after 1970 (see later).

Turning to the area for the cultivars grown each year, this was recorded by the District authorities when grain was delivered at harvest, but unfortunately individual cultivar records were only located for the 1969 harvest to 2019 one. Some assumptions (see later) were made for the period 1960–1968. Each year, the relative area of each cultivar was multiplied by the relative PY, values were added and then divided by the sum of all relative areas (usually exceeding 0.96) to give the aggregate VYI for the particular year. If 100% of the area had been planted to Siete Cerros 66, the VYI would have been 100. Note that vintage trials are side-by-side comparisons and are not confounded by trends in Tmin or in atmospheric CO_2, unless cultivars interact strongly with these factors, which is unlikely. Following the simple methodology outlined earlier, breeding progress in farmers' fields came from the difference in VYI in the first and last three years of each 20-year period, expressed relative to the mean VYI for the period.

Since the FY data began in 1960, and semidwarf cultivars were first grown two years later, it was important for a complete analysis to estimate VYI beginning in 1960. Given the methodology adopted, an average value for 1960–1962 would suffice and this was obtained from old incomplete area records, along with PY data from early vintage trials, which always contained two important representatives of final tall cultivars (Yaqui 50 and Nainari 60, see later).

2.3. Cultural practices and off-farm factors (agronomy+)

Estimating agronomic progress directly from factor levels, as was attempted recently by Rizzo et al. (2022), would have been impossible here given the lack of continuous agronomic data for the Yaqui Valley and FY influences of off-farm issues (see later). However, dividing the breeding progress component into the climate-corrected yield progress gave us the remaining sources of progress, namely agronomy, but confounded by these issues (hence agronomy+). Dissecting and understanding the agronomy+ component of yield increase benefited from several sources. Surveys of wheat agronomic practices had been conducted across the Valley by CIMMYT in 1981, 1982, 1985, 1989, 1991, 1994, 1998, 2001, 2003, 2008, 2010 and 2013 and are available in CIMMYT Publications. Starting with 93 farmers in 1981, as described in Traxler and Byerlee (1992), all but the 1991 survey (Meisner et al., 1992) returned to the same locations in the Valley and collected data from whoever was farming the block. Surveys are supplemented by satellite surveys of field yields and of some agronomic practices for some years (1994, 2000–2008). Cultural practices, their changes and improvement across years (but only 1981–2008) are summarized and discussed in detail by Traxler and Byerlee (1992) and Ortiz-Monasterio and Lobell (2012), and from a somewhat different but useful perspective by Flores (2020), who was intimately involved in all farmer data collection. In addition, the book of Matson (2012) has excellent commentary on socioeconomics and the resource base between 1980 and 2008, the "plus" part of agronomy+ , being the results of a Stanford University project. The price of wheat and agricultural inputs in Mexico over the study period are important variables underpinning farmer practices and were obtained from official sources.

3. Results

3.1. Climate-corrected yield increase

The first row in Table 1 presents the FY divisors for calculating the temperature-corrected annual % rate of increase in each 20-year period, including in the final column, the whole 60 years. The second row in Table 1 shows the temperature-corrected technological progress in each period (as in Fig. 1b).[5] Allowing for the positive influence of CO_2 increase (third row) gives the rate of climate-corrected yield increase (fourth row).

3.2. Breeding component of technological progress 1960−2019

Of the many varieties released in the Yaqui Valley between 1962 and 2018, 48 reached 3% or better of harvest area in at least one year from 1969 onwards (Supplementary Table 2). Twenty-one rose to at least 30% in one year, and 7 at least 50%, namely INIA 66, Jupateco 73, Nacozari 76, CIANO 79, Altar C-84, Jupare C-01 and CIRNO C-08.[6] Two other varieties fell between 30% and 50% (Opata 85 and Rayon 89) but

Table 1
Measures of yield increase (%, p.a., see text) in wheat farm yield (FY, kg/ha) in the Yaqui Valley for each 20-year period between 1960 and 2019, and for the whole 60-year period.

Measure	Period			
	1960–79	1980–99	2000–19	1960–2019
Average temp-corrected FY for period, kg/ha	3545	5409	6118	5024
Temperature-corrected FY increase, % p.a.	4.30	0.64	1.81	1.68
Effect of CO_2 increase, % p.a.	0.13	0.17	0.22	0.18
Climate-corrected increase in FY, % p.a.	4.17	0.47	1.59	1.49
Breeding progress in farmers' fields, % p.a.	0.97	0.49	0.71	0.70
Yield increase from agronomy+ , % p.a.	3.16	-0.02	0.87	0.78

[4] Note percentages of components multiplied to give a total measure were separated not by subtraction but by division, although with multipliers close to 1.0 it makes little difference.

[5] Note that despite the simpler approach to calculating slope, values were almost the same as those presented in Fischer et al. (2022), namely 4.5%, 0.59%. and 1.77% p.a. for the three 20-year periods, respectively

[6] Varieties are named in Mexico such that the suffix refers to the year of release while the C preceding the year denotes a durum wheat

were notable because they persisted for many years. Durum wheat first appeared in the record in 1977 (Mexicali C-75). Durum area rose irregularly from then due to its resistance to Karnal bunt (*Tilletia indica*), which became significant in the Valley around 1992 and later, and to market opportunities.[7] The durum area exceeded 60% of the harvest area by 1995 and thereafter often exceeded 80%. The first semi dwarf durum variety comparable in yield to semi dwarf bread wheat of the same vintage was Cocorit C-71, although it was never widely grown. From then on however PY of durum varieties kept up or even exceeded those of bread wheats, and the two species are analysed here together as their overall PY progress, the product of breeding, was similar.

The many vintage experiments measuring PY progress are summarized in Fig. 3a showing relative PY values versus year of release for the more important 41 of the 48 varieties between 1968 and 2019 (full details are in Supplementary Table 2). PY progress, relative to Siete Cerros 66, was 0.56 ± 0.05% p.a., while for the key 7 varieties of the 41 mentioned above it tended to be higher (0.81 ± 0.10% p.a.),[8] being strongly influenced by the last three releases (all DWs), although the last major BW release (Borlaug100 2014) has a PY comparable to the highest yielding DW (Cirno C-08) and was adopted on 13% of the area in 2019 (and 35% in 2020).

The relative PYs in Fig. 3a (along with estimates for the handful of missing less important varieties recorded as exceeding 3% of area in at least one year) were used to calculate the VYI for farmers' fields for each year. Fig. 3b shows how this index of breeding progress evolved from 1969 to 2019. Over the total 51 years the VYI showed a linear slope of 0.63 ± 0.026% p.a. relative the yield to be expected with 100% Siete Cerros 66. It was intermediate between the two slopes of Fig. 3a. To extend the breeding analysis back to 1960, PY of the last dominant tall varieties were well known, being 79% for Yaqui 50% and 89% for Nainari 60 (e.g., Fischer and Wall, 1976). Assuming 50:50 occupancy of area in 1960–62, estimates the VYI in 1960–62 to be 84, shown separately on Fig. 3b.

VYI advanced in fits and starts (Fig. 3b), as has been commonly noted by breeders. In the last 25 years in the Yaqui Valley, this partly reflects domination by three successive outstanding durum varieties: Altar C-84 from 1996 to 2003 (except 2002), Jupare C-01 (2004 – 09), and Cirno C-08 (2012–19). In fact, the index jumped from 117 to 129 with the rapid adoption Cirno C-08, which went from 1.4% of the wheat area in 2011 to 71% in 2012; it has an estimated relative PY of 128.8%, slightly ahead of the best bread wheat, Borlaug100–14 at 126.7%. This irregular progress at the farm level supports the simple methodology adopted here to calculate progress. Combined with the above assumptions regarding VYI in 1960–62, it resulted in the following estimates of breeding progress: for 1960–79, 1980–99 and 2000–19, respectively 0.97%, 0.49% and 0.71% p.a. (Table 1).

3.3. Agronomy+ component of technological progress

Yield increases due to agronomy+ fluctuated notably across the three 20-year periods and appears to explain the slowdown in FY growth in the middle 20-year period (Table 1). This had been noticed and explored in the 1991 survey of Meisner et al. (1992), but unreported has been the subsequent recovery in agronomy+ (and in FY growth) in the last 20-year period. Clues as to causes of FY changes may be found in the surveys of farmer practices. Unfortunately, there were no formal surveys before 1981 nor after 2013. Moreover, several survey reports go into much more detail than is possible here (Byerlee and Flores, 1981; Meisner et al., 1992; Ortiz-Monasterio and Lobell 2012; Traxler and Byerlee, 1992).

Changes in some agronomic practices and socioeconomic features are summarized in Table 2. Not shown is the seeding date and rate. The former, recommended to be between 15 November and 15 December, averaged 10 December but was more often in early December than late November,[9] and showed no trend since variety duration changed little. There was also little change in seeding rate (around 150–170 kg/ha), except in the early years with raised beds, when only 50 kg/ha was recommended (see below).

The dominant change in agronomy was N fertiliser use, which rose steadily (Table 2, Fig. 4), although currently rates appear to have stabilized at around 300 kg N/ha. Most N was incorporated pre-sowing but splitting with sowing and post-sowing applications have increased; anhydrous ammonia and urea are the dominant forms used. P fertiliser rates have been unchanged at 46–54 kgP_2O_5 /ha but the % of farmers using it has steadily risen to close to 100% (Table 2), such that total P use across the Valley has increased significantly. Almost all irrigation is flood or furrow irrigation, and the number of irrigations (counting the pre-sowing one) has declined slightly (Table 2). Herbicides arrived in the 1960 s, and by the first surveys, all farmers used them, mostly for broad leaf weeds (Table 2), but a lower and variable number apply against grass weeds as well. To aid grass weed control, pre-irrigation and sowing into cultivated moist soil (*siembra sobre humedad*) was adopted by 40% of farmers by 1980 (Byerlee and Flores, 1981). Greater than 95% of farmers now use insecticide against aphids despite some acceptance in

Table 2
Key descriptors from the farmer surveys showing changes over time.

Descriptor of wheat cropping	Survey dates[a]				
	1981, 1982	1989, 1991	1998, 2001	2008, 2010	2013
N fertiliser use, kg/ha	186	226	254	257	303
Farmers using P fertiliser, %	57	71	84	83	97
Number of irrigations (incl presowing)	4.35	5.0	4.25	4.3	4.1
Herbicide for broad leaf weeds, %[b]	85	84	92	82	91
Herbicide use for grass weeds, %[b]	17	8	8	14	45
Wheat not preceded by summer crop, %	42	72	89	90	89
Sown on raised beds	7	48	86	82	83
Land tenure, number of ejidatarios[c], %	55	57	32	21	26
Land tenure, number of private owners[d], %	39	37	35	44	55
Land tenure by number, renters, %	6	6	33	35	19
Decision-makers with tertiary degrees, %	12	23	33	53	63

[a] Where two years shown, average of survey results are given
[b] Those who used herbicides for both weed types are included in both rows
[c] The ejido system of land utilization meant farmers were given access to small parcels of land (10–20 ha each), which was farmed individually or collectively, but ownership remained with the Government.
[d] Including *colonos* who were a small number relative to private *proprietarios*.

[7] The North American Free Trade Agreement (NAFTA) effectively made Yaqui bread wheat uncompetitive in most Mexican locations due to rail freight costs favouring imported US bread wheat. Fortunately, there was a good world market for durum wheat and a port nearby to the Yaqui Valley (Guaymas)

[8] The lack of progress 1995–2005 in Fig. 3a seems to challenge the notion of steady PY progress. However, a more likely explanation is the release of several BWs that performed well on beds with large furrow gaps, a testing system introduced by breeders around 1990, but did not perform well where gaps were smaller (see Fischer et al., 2019). The beds system was modified by breeders in the late 1990 s, reducing gap size (see later).

[9] Recommended sowing date was extended further to 15 December in the 1980 s (Traxler and Byerlee, 1992) with no effect on actual average date which was 10 December (range 5–16 December, over 17 survey years 1981–2013).

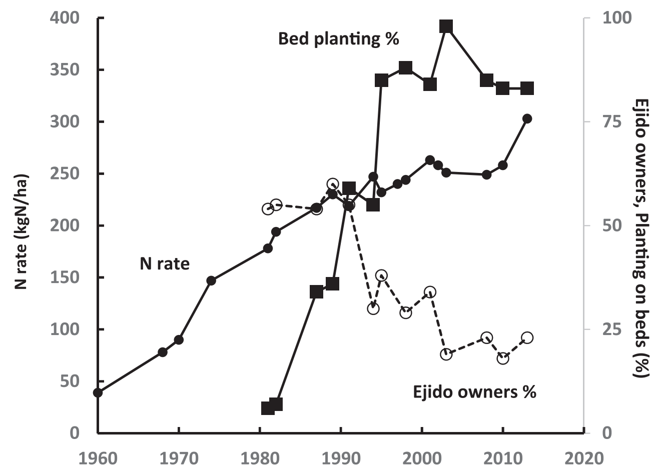

Fig. 4. Change in nitrogen fertilizer use, bed planting, and ejido ownership for wheat in the Yaqui Valley between 1960 and 2019 and as determined by farm surveys from time to time.
Source: various CIMMYT published and unpublished surveys.

the 1980 s of IPM strategies (Traxler and Byerlee, 1992) and continuing official distribution of biocontrol agents. Fungicide is used to combat the only significant foliar disease, namely leaf rust (*Puccinia triticina)*, in those few years when new strains overcome host-plant resistance, and lately has become more common on the widely grown durum variety CIRNO C-2008 whose resistance was overcome in 2017 by a new race.

Another major change across the survey period was that wheat not preceded by summer crop (essentially following summer fallow) has steadily increased (Table 2), as the cropping intensity has declined over the study period due primarily to water shortages, markets, and in the case of the commonest summer crop, soybeans, an insect pest. Soybean was 52% of the wheat area in 1981,1982 surveys, and probably higher in the previous 20 years, still 58% in 1991, but close to zero by 1996 and thereafter, due to invasion by the silverleaf white fly (*Bermisia argentifolii*) in 1994. Cotton has also declined notably, with winter-spring maize now comprising the main alternative crop in winter-spring. Winter-spring crops displace wheat, but never exceeded 50% of the wheat area due to low and uncertain profitability. In terms of cultivation practices, for wheat following wheat the straw was at first usually burnt ahead of land preparation[10]; however, by 2008 and afterwards, > 95% was incorporated by cultivation.

A major new agronomic innovation was introduced by CIANO in 1980, namely sowing wheat on raised beds (surcos or camas in Spanish), with centers spaced at 75 or 80 cm, and irrigation only down the inter-bed furrows (Moreno, 1986). Bed planting steadily increased from then to exceed 80% by 2000 and thereafter (Table 2, Fig. 4). Raised beds bring several cost-savings, but especially easier weed removal (mechanical and in the early years by hand) and better water control as well as reduced lodging risk (Sayre and Moreno Ramos, 1997). Beds in turn also facilitated another major agronomic switch already mentioned, namely from the traditional dry sowing followed by irrigation, to sowing wheat into pre-irrigated fields. Pre-irrigation, fresh bed preparation, followed by *siembra sobre humedad* became very popular, exceeding 95% of sowings in 1991 (Flores and Aquino, 2001) and thereafter stayed high. However, seed rate remained remarkably stable at around 160 kg/ha, well above that recommended for beds (50 kg/ha).

[10] When soybean followed wheat, burning the wheat straw was considered essential to allow planting without delay.

Turning to off-farm developments, following major policy reform in the early 1990 s,[11] making it possible to rent or even sell ejido land, there have been large changes in land tenure (Table 2, Fig. 4) with the steady decline of the traditional smallholder *ejido* system and rise in rented wheat land; the third category, private land, varied between 23% and 55%. Byerlee and Flores (1981) reported that in 1981 the whole Valley had an average farm size of 14 ha (individual ejidatarios), 660 ha (collective ejidos with 5 ha per member) and 27 ha (private farmers). Their 1981 survey found that some 50% of the private farmers, but no *ejidatarios*, had more than 70 ha each. In contrast, the final survey in 2013, 32 years later, average operational farm size had increased substantially: ex-ejidatarios 140 ha, private owners 301 ha, and renters 372 ha; all categories had a large range in sizes, going up to around 1500 ha. By 2013 only 13% of land was with ejiditarios, while 61% was private and 26% rented. Also, the proportion of operators with tertiary qualifications had risen notably (Table 2), while farmer age crept up from 48 years in 1998 (not recorded in earlier surveys) to 55 years in 2013. By then greater than 90% of all farmers used credit and technical assistance; the private credit suppliers had become a major force in technical advice and input supply to farmers (McCullough and Matson, 2016).

In the 60-year study period and coinciding with onset of the demise in the *ejido* system, clearly the biggest policy upheavals were the withdrawal of government support for agriculture around 1992, culminating in the enactment NAFTA in 1994, as described by Naylor and Falcon (2012). Input subsidies and price support were reduced or eliminated; government involvement in rural credit, fertilizer manufacture and agricultural extension was also reduced, and irrigation system management decentralized. The impacts on prices of wheat and inputs, and on risk, were generally negative. The real wheat price, which had been considerably higher than the that in USA up to the mid-1970 s, a period of high subsidies and generally favourable exchange rates, came closer to this world price indicator by the late 1990 s, and followed it reasonably closely thereafter (Fig. 5a). Important was the rise in wheat prices in Mexico after about 2006, in line with world wheat prices. The cost of N fertilizer – measured in terms of output: input ratio – remained around 2 kg of wheat/kg N from the mid-1970 s until 1990 due to subsidy, but by 1995 it had risen to 3.3; by comparison throughout this period it was around 6 kg/kg N in countries exposed to the world market like Australia or Argentina (Rejesus et al., 1999). Water price was also generally low, even after decentralization, subsidy removal, and price rises in the early 1990s, with operational costs being assumed by farmers. A more complete picture of assistance to wheat producers but excluding the influence of world price and exchange rate changes, is support for wheat as a percentage of farm gate value calculated by OECD, considering both price support as well as all input subsidies (Fig. 5b). Data are only available from 1986 but show wildly fluctuating but generally negative support until the late 1990 s, followed by fluctuating but generally positive support after 2000.

4. Discussion

4.1. The breeding component of technological progress

For comparisons with other studies, the rates of PY progress in Fig. 3a are better calculated relative to the PY predicted by the linear model in the final year of any series, in the case here rates for 2019 are reduced to 0.57% p.a. (7 most popular vars) and 0.43% p.a. (all vars). The higher number is comparable to the average rate similarly calculated across 20 wheat studies published since 2010, which, excluding the Mexico

[11] This came after a boost to the ejido system in 1976 with land reform, raising ejido area by 43,000 ha or about one fifth of the Valley, through new collective ejidos, each having 660 ha and around 65 farmer members (Byerlee and Flores, 1981)

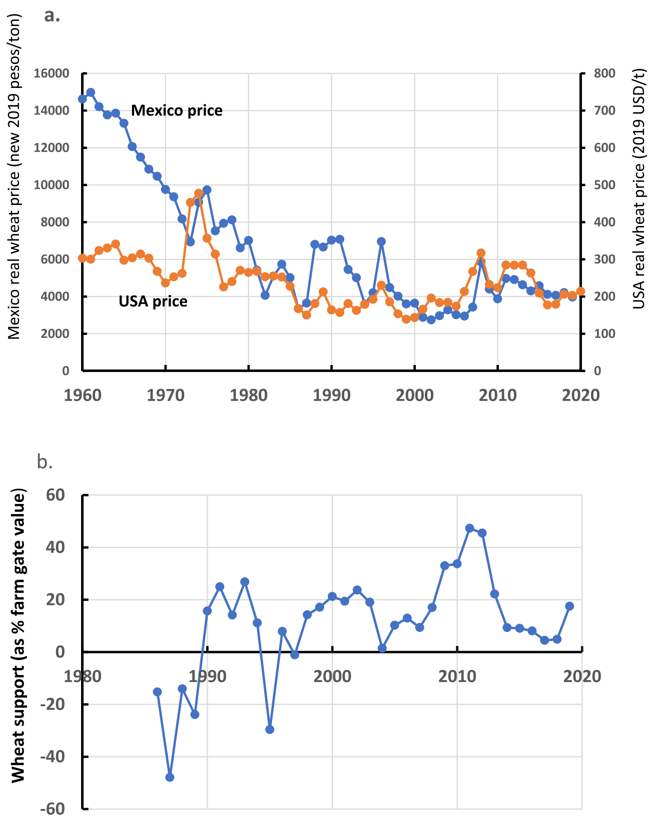

Fig. 5. a. The evolution of real wheat prices in Mexico (Mexican 2019 new pesos per ton) and USA (2019 USD/t) over study period Sources: Mexico nominal wheat prices for 1960-90 from INEGI, (inegi.org.mx/app/biblioteca) Estadísticas históricas de México 2014. 2015. Cuadro 9.37), for 1991-2020 FAOSTAT; all corrected for GDP inflation from the World Bank. USA HRW real prices from World Bank. b. Wheat commodity support in Mexico (Producer Single Commodity Transfer, PSCT, % farm gate value).
Source: OECD statistics, http://stats.oecd.org (accessed November 2021)

studies, was 0.58 ± 0.045% p.a. (Fischer, 2020).

Calculating the VYI (Fig. 3b) is a simple way to include the important effect of variety area adopted by farmers. The Valley is characterised by rapid adoption of superior varieties: for the seven outstanding varieties of the study period, they were at 50% of peak adoption by three years after release, and within 5% of their peak in five years. In agreement with this, Brennan and Byerlee (1991) reported the average age of all varieties grown to be less than four years, the lowest of seven global situations they studied. Also critical is that on-farm variety trials in the Valley over many years (K. Sayre and I Ortiz-Monasterio unpublished) confirm the assumption in the VYI approach that yield relativities of varieties in farmers' fields matched those reported in Fig. 3a in breeders' plots. Large interactions (e.g., rank changes or cross-over interactions) could theoretically arise where farmer fields yield less than half of PY, for example, being very weedy, poorly watered, January sown or diseased, but this was never the case. Robust disease management, largely through resistance but also in some years through fungicide, was another factor maintaining PY relativities on farmers' fields.[12] In the whole 60 years, the most significant disease outbreak was leaf rust in 1977 on susceptible varieties, estimated to have reduced FY by 23% (Fischer et al., 2022). There were also lower-level losses on the durum variety Altar C-84 in 2001–2003 (Singh et al., 2004). On no other occasion was FY likely to have been reduced more than 5% by the infrequent and localized rust epidemics, with fungicide aerially applied should significant rust appear. Finally, variety × year (weather) interactions can arise, but for varieties in vintage trials in the Yaqui these were generally quite small (e.g., Sayre et al., 1997; Ortiz Monasterio et al., 1997; Honsdorf et al., 2018; Mondal et al., 2020).

Other variety × management interactions can influence FY increase over time such as changes in weed control, N fertilizer rate, and for the Yaqui Valley, the shift to sowing on raised beds. Weed control may be a unique factor, for PY breeding progress in wheat has inevitably reduced its weed competitiveness (e.g., Sadras and Lawson, 2011). Thus, effective means of weed control are essential for the realization of PY progress in farmers' fields. The fortuitous arrival of herbicides in the 1960 s, first for broad leaf weeds then for grass weeds, as well anecdotal local evidence of their rapid and widespread adoption (but still lagging in the case of grass weed herbicide use in 1981, see Table 2) all point to the key role of herbicides in protecting yield gains of modern wheats. The other two possible interactions, N fertilizer and bed planting, are however more relevant to understanding FY gains.

Improved PY was initially accompanied by an improved response to nitrogen, a positive G × N interaction, as seen in Ortiz-Monasterio et al. (1997). In the approach used here (vintage trials run at best agronomy of the latest vintage), any G × M component is included in the measured PY progress (Fischer, 2016), and hence in the VYI in farmers' fields. However, it was artificially muted in the early vintage trials because lodging protection was provided and aided the older taller varieties, for example leading to the high relative PY of two of the last tall varieties (mean of 84% of Siete Cerros 66). Early in the 1960–79 interval, nitrogen fertilizer use by farmers was relatively low (40 kg N/ha, Fig. 4), partly because of the lodging risk with tall varieties, but by 1979 it had increased to 175 kg N/ha following the complete disappearance of the last tall varieties by 1965. Because of the lodging protection, the positive variety × N interaction would have been partly missed by the breeding progress of 0.97% p.a. in Table 1 and became part of the high agronomy+ component (3.16% p.a.): together these effects well characterize the Green Revolution in irrigated wheat. The G × N interaction was unlikely to have been very important in the following study period (see Bell et al., 1995) by the end of which N rate had risen to around 250 kg/ha, and to have been negligible in the final study period with very high N applications and only quite recent varieties grown.

The bed planting which replaced basin or close-spaced furrow irrigation from the early 1980 s reaching 90% of the wheat area by 2000 (Fig. 4), brought notable management and cost advantages (Sayre and Moreno Ramos, 1997). There were also interactions with variety, discussed extensively in Fischer et al. (2019). The initial recommended bed system (usually 2 rows per bed 30 cm apart, beds commonly spaced 80 cm) had furrow gaps (50 cm) large enough to reduce the yield of many short and/or erect varieties grown then (like Oasis 86, Bacanora 88, Achonchi C-89). In farmers' fields following the recommended system, breeding progress on beds may have initially been set back somewhat relative to that estimated in Fig. 3a (which generally avoided bed trials for characterizing the PY progress of varieties). This agrees with the detailed survey of 1991 (Meisner et al., 1992), which found that the size of the canopy gap around heading was the strongest (negative) predictor of yield, followed by weed score, with weediness often associated with gap score. This may explain why farmers from their own experience switched to three rows per bed or more seed (initially in 1981 around 75 kg/ha, by 2001 135 kg/ha (Flores and Aquino, 2001) and 162 kg/ha in the 2013 survey), not that the seed rate increase was ever found to reduce the interaction due to large interrow gaps (Fischer et al., 2019). The Flores and Aquino survey reported that farmers even planted a row in the furrow, the practice beginning in 1991 (14% of all

[12] Over time released varieties can lose disease resistance: any FY loss as a result is not attributed to breeding for PY as generally defined, but to management failures.

bed planting) and reaching about 28% at the end of the decade. This defeats several advantages of the bed system but also suggests that farmers believed that large furrow gaps reduced yield.[13] Meanwhile, in the mid1990s, as a cost saving measure, breeders also adopted the original bed system for yield testing. However, by 2000 they had shifted to narrower furrow gaps, but not before that they had released some varieties that showed significantly higher yield progress under the original bed system (Fischer et al., 2019). These interactions (variety vs planting system) were probably too small to affect FY performance much, and the main effect of the switch to beds in the late 1980 s, an initial yield-reducing effect, while belonging to agronomy+ , should have disappeared by 2000 (see also 4.2).

We can conclude that breeding (including any small positive G × N component early on not accounted for in the VYI of 1960–79) overall contributed about half of the technological progress in FY across the 60-year study period (Table 1); this agrees well with several other studies of this question mentioned in the Introduction. VYI estimates PY improvement, but this is not the only contribution of breeding to productivity. Almost of equal importance is "maintenance" breeding, defending wheat against the inevitable evolving races of diseases, in particular the rusts, and in the Yaqui Valley, the arrival of Karnal bunt, ongoing efforts which have been singularly successful (Smale et al., 1998). Finally, breeding also focuses on quality traits, and the bread-making quality of Yaqui Valley bread wheat varieties, despite unchanged protein concentrations, has improved notably even as PY has increased (Guzmán et al., 2017). There have also been improvements in durum wheat quality, with a higher semolina pigment content in releases of the last decade.

4.2. Crop management in technological progress and off-farm factors

In contrast to the clear-cut VYI for estimating breeding progress in FY, the estimate of agronomy progress carries more uncertainty since it is determined by difference, and agronomy+ picks up intangibles such as managerial skill and all the external factors which can impact on FY already mentioned in Results.[14] It is therefore remarkable that a linear function of time (year) captures so much of FY variation over each 20-year period studied (Fig. 1). Equally interesting is the marked variation in the agronomy+ slope between periods (Table 1). Thus, the overall contribution of management was close to half of total true technology gain (Table 1, 1960–2019), but one which was very high initially (1960–79), then zero (1980–1999), and finally high again (2000–19).

Dealing firstly with agronomic technologies, notoriously difficult to unravel and sometimes reducing costs rather than lifting FY. Over the whole 60-year study period the recommended optimal and the actual sowing date and seed rates showed no change. Late sown fields (after 15 Dec, delays due to rain) only sometimes reduced FY (e.g., in 2000, Ortiz-Monasterio and Lobell 2007), but not always (e.g., 1991, Meisner et al., 1992, or 2002 and 2003, Ortiz-Monasterio and Lobell 2007). Nevertheless, as already seen, some agronomic factors changed substantially (Table 2, Fig. 4) and were important for FY as will be discussed now by 20-year periods.

The first 20 year period (1960–1979) corresponded to the Green Revolution.[15] Crop land ownership, divided about equally between private and ejido small land holders, was reasonably stable, except for the new collectivized *ejido* land in 1976 following land expropriation (35,000 ha). Input and product prices were controlled by the Government to help farmers (Naylor and Falcon, 2012) as seen in the generally very favourable wheat prices then (Fig. 5a). Thus, despite inefficiencies of the *ejido* system, all farmers rapidly adopted the new semidwarf varieties (first release 1962, full adoption by 1966), and were equally keen to take on associated agronomic technologies, in particular increasing N fertiliser from 40 to 175 kg/ha over the period (Fig. 4). They had been providing suboptimal N levels in the early 1960 s because of the lodging susceptibility of the tall wheats, hence the rapid rise in N use once the lodging resistance of the semidwarfs was accepted; this was clearly the largest management improvement in the period. FY increased 3150 kg/ha between 1960 and 1979 (Fig. 1b). Use efficiencies for N fertilizer measured by Ortiz Monasterio et al. (1997) suggest that the 135 kg/ha increase in N fertilizer alone is enough to explain at least two thirds of the FY increase, once the 20% rise in VYI is accounted for. Weed management was a special problem in this period of increasing N fertilizer with less competitive semi-dwarf wheat varieties, hence the gradual adoption of herbicide control of broadleaf weeds (reaching 85% of fields by 1981,82, Table 2) would probably also have been of some importance for the observed FY increase. Grass weed herbicides came later, therefore were less well known and used (only 11% in 1981), such that around 1980 grass weeds were moderately serious with wheat after wheat, especially with dry sowing (Byerlee and Flores, 1981). The dominant rotation was wheat-soybean double cropping, but there was some cotton and safflower, and this appears not to have changed much in the first 2 decades, helping weed control in wheat.

In the second twenty-year period (1980 −1999) N use continued to increase but at a slower rate, and planting wheat on raised beds was adopted (Fig. 4). The latter was discussed in detail in 4.1 with respect to possible variety interactions, with effects on FY likely to have been small in the long run. However, three other aspects of bed planting may have affected FY. As mentioned, bed planting facilitated sowing *siembra sobre humedad* after an irrigation some 20 days earlier. A second positive factor with bed systems was better water management which should have helped as water shortage increased towards the end of the 1990 s. This required farmers to bring forward the timing of the first post-sowing irrigation to no later than 60 days after the pre-plant irrigation (Lobell and Ortiz-Monasterio, 2008). The third effect of beds arose because the irrigation before planting (*siembra en humedad*) meant earlier pre-irrigation pre-plant application of much of the N fertilizer (Ortiz-Monasterio and Lobell, 2012). These authors point out that this is an inefficient use of N due to the even earlier application further increasing N losses. The additional effects on yield of the introduction of bed planting are therefore complicated but on balance it probably contributed little to FY change in 1980–99, but reduced costs, especially weeding and watering ones, and at least initially seed costs (Traxler and Byerlee, 1992). Yields of a limited number of surveyed fields across the period support this, with beds yielding on average 8% more than traditional plantings (Flores and Aquino, 2001), but without controlling for other management factors.

Another big change in agronomy in the second period was the decline in soybean area to almost zero in the mid-1990 s and thereafter due to the white fly infestation (Table 2). Also there were very small areas of other spring-summer crops like cotton or warm-season maize. This loss of crop rotational diversity is likely to have negatively affected wheat yields (Kirkegaard et al., 2008). With most wheat planted on summer fallow from the mid-late 1990 s a related problem was identified. Using remote sensing Ortiz-Monasterio and Lobell (2007) found that wheat after weedy summer fallow in 2002 and 2003 (around 37% of all wheat) suffered a 12% yield loss (720 kg/ha) compared to a non-weedy fallow. This effect alone is likely to have decreased FY 4% or so in the last years of the 1990 s

Considering all the changes in on-farm agronomy described above for the second period, it did not seem to deteriorate in a manner which

[13] They also believed that the plant row in the furrow advantageously slowed water movement (Flores, 2020), erroneously it turns out (I. Ortiz Monasterio, pers comm.) probably because these plants tillered little.

[14] Not mentioned were annual crop area changes. In a region like the Yaqui Valley, which recognizes small but consistent variation in soil quality for wheat productivity, they can influence FY (e.g., area contractions can see poorer soils not cropped) but no evidence was found for this (Fischer et al., 2022).

[15] It is notable that FY had increased about 5% p.a. in the decade (the 1950 s) preceding the first semi-dwarf varieties (the Green Revolution).

would stop wheat FY progress altogether from this source, as seen for agronomy+ in Table 3. Undoubtedly the biggest negative changes slowing FY growth in this period were the off-farm policy ones described in Section 3.3, namely the withdrawal of much government support. A period of disruption followed which is likely to have initially negatively impacted crop management, possibly through to the end of the decade. More significantly in the short-term, farmers were now more exposed world wheat prices, which were low and falling in the late 1990 s and, although the floating of the Mexican peso in 1995 and the brief global price peak in 1996 helped, wheat prices reached their lowest ever real values by the turn of the century (Fig. 5a) so profitability was low in the late 1990 s (and into the early 2000 s, Naylor and Falcon, 2012). Following the law change in 1992, by the end of the 1990 s many *ejidatarios* had rented or sold their land (Table 3). Agronomically the above cost-price squeeze can be seen in a slowing of the rate of increase in N fertilizer use in the late 1990 s (Fig. 4), a profitable input for the higher PY varieties coming from breeding.[16] It is likely there were corresponding consequences for FY growth for, although on average the Valley appears to be using adequate N, surveys always revealed that a small but significant number of fields were N deficient. Also researchers measured high N losses, especially with the new system of *siembra sobre humedad* (Ortiz-Monasterio and Lobell, 2012).

As noted, there was a significant discontinuity in the temperature-corrected FY ahead of the final 20-year period (Fig. 1b), amounting to a drop in FY of around 500 kg/ha in 2000. This is explained by the YVI in the first 4 years of the 2000–19 period showing no progress (Fig. 2b) along with no agronomy+ progress as well, probably because the price environment remained very unattractive. Also water shortage were beginning to appear at the end of the 1990 s but the effect was largely on cropping area. A clearer break in temperature-corrected FY values may have been between 2003 and 2004 (Fig. 1b), but it would not have altered estimated annual rates of progress for the third period significantly. Thus, the final 20-year period (2000–19) saw (at least after 2006) a return to a large agronomy+ component (0.87% p.a. overall) of FY growth, having a proportional impact on total yield advance about equal to that of breeding (Table 1). Unfortunately, the period fell partly outside that studied by Matson and colleagues and encountered changed CIMMYT priorities, limiting the collection of farm agronomy data.

By 2008 *ejidatarios*, with their inefficiencies, had fallen to 21% and farmers with professional degrees had risen to over 50% (Table 3). It is likely this was followed by an improvement in skills of land managers and access to more timely credit and inputs and better technical assistance, accompanied by a gradual consolidation of operational scale as reported in Section 3.3. The especially strong links developed between larger farmers and credit suppliers already mentioned, the latter essentially replacing public extension over the last 25 years (McCulloch and Naylor 2016), was a key part of these changes. Along with the new more stable policy environment, there were much more favourable wheat prices after 2007 (Fig. 5a), when real world wheat prices rose sharply, with further rises around 2011–12, and have since stayed at least 50% above the lows of the late 1990 s and early 2000 s. Finally, another development assisting wheat, if not so clearly FY progress, was the turn-around in water supplies. After a long period of low rainfall (1996–2004) and reduced water supply from the dams, culminating in dramatic wheat area cuts in 2004, supply improved, wheat area bounced back in 2006 to exceed average for the rest of the period.[17] In addition, water management was benefitting from the Government's policy of decentralization to local control, supported by increased but still modest water prices to cover this cost, beginning around 1998 (Naylor and Falcon, 2012).

The above external factors would all have helped a recovery in the standard of crop agronomy (e.g., better timeliness and precision of all operations) and in FY. Clearly the use of N fertilizer reached its highest levels (Fig. 4) as farmers sought to benefit from higher wheat prices and produce durum wheat at high protein and reap the small premium demanded by the world market. Summer cropping (e.g., soybean and cotton) had largely disappeared but cool season maize for feed was steadily increasing. Wheat planting on beds, usually laser levelled, had remained at over 80% of the wheat area. FY losses due to disease, weed, and insect problems were minor, except for some leaf rust 2001–2003.

In summary since the 1960 s the Yaqui Valley had undergone a unique transformation from an irrigated wheat cropping system of mixed small holders and subsidies, not unlike the Punjab of South Asia or Egypt today, plus some medium and large farms, to one of much larger operational and mechanization units with less labour, delivering over three times the wheat yield at world prices. It has made the transition seen in developed countries, becoming similar in many respects to the irrigated wheat lands across the border in California and Arizona. But in fact, the modern varieties and agronomic practices of the Yaqui Valley differ little from those of small holders in the Indian Punjab state, who have also better than tripled yields in the same period to reach around 5 t/ha, or those in Egypt with a national wheat yield close to 6.5 t/ha (Fischer et al., 2014).

4.3. Reflections on the way forward for yield

Where is wheat yield (FY) in the Yaqui Valley heading in the next 20 years or so, the period of greatest challenge for global food security as argued by Fischer and Connor (2018)? One estimate is the projection of growth numbers from 2000 to 19 in Table 1, expressed relative to 2019 FY for greatest relevance, namely for breeding (VYI) progress 0.66% p.a. and for agronomy+ 0.80% p.a., together giving 1.47% p.a. However, agronomy+ contained off-farm stimuli which are unlikely to recur, especially the 50% increase in world wheat prices in the period (Fig. 5a). Yield price elasticity is difficult to know in any situation (Fischer et al., 2014) but at only 0.1 it would have added 5% to FY increase 2000–19, or 0.25% p.a. This reduces FY predicted future growth to 1.22% p.a., which we round off to 1.2% p.a. as our best still uncertain bet for the next decade or two based solely on recent progress. The rate of increase in world wheat yield (1.32% p.a. over 2000–2019 relative to the predicted global mean yield in 2019 of 3.51 t/ha, $R^2 = 0.927$, Fig. 1a, FAOSTAT, accessed October 2021) barely meets demand, not preventing recent wheat area increases and just holding real prices reasonably steady[18]; greater FY growth would be very desirable for obvious reasons. Predicted Yaqui Valley yield growth at 1.2% is now below the world number, but as an important "bellwether", prospects for lifting this rate are now discussed briefly.

FY increases through PY increase, and through yield gap closing faster than PY is increased. Dealing with gap closing first, the earlier paper (Fischer et al., 2022) estimated that the FY gap was about 24% of PY in 2019, or 30% of FY. These are small gaps, which economics suggests will be difficult to close further and, in contrast to many other developing countries, there is almost no yield gap due to slow variety adoption. As has been discussed, the Valley seems to have refined the agronomy of irrigated wheat to the extent seen in other wheat regions with such high yields (e.g., Western Europe). Nevertheless, there is surprising spatio-temporal variation in FY at the field level, as can be studied nowadays from satellite imagery and highlighted for the Yaqui Valley initially by Lobell et al. (2002). Across 3 years around 2000, estimated field FY in the Valley shows an average interquartile range of about 1.6 t/ha (or 26% of average FY), with a negative skew.

[16] This doesn't mean the varieties needed more N, rather their economic optimum N uptake was always increasing as PY increases, at approximately 30 kg N/ha per ton/ha PY increase.

[17] Area was 179,000 ha (2003) and the two following years 26,000 and 89,000. before recovering to 164,000 ha.

[18] An assessment before the uplift in world wheat prices due to Covid 19 and other disruptions beginning in early 2022.

Consistently the FY range across fields seems to be partly related to a small proportion of fields with inadequate N supply or very late sowing (January), something which could be rectified. However, luck and risk in decision making in the face of uncertain seasonal weather may also be a factor, even with good managers and assured water at planting (Lobell, 2013) and arising from the year × agronomy interaction due to annual variation in weather. This issue deserves more attention, for example using seasonal weather forecasting (e.g., Ramírez-Rodrigues et al., 2016) ,[19] or a profit-risk-utility framework as applied to irrigated wheat in eastern Australia (Monjardino et al., 2022). A second opportunity is the lack of rotational diversity, with much wheat planted after summer fallow, in turn following wheat. Global evidence suggests inserting other crops, especially broadleaf ones, will lift wheat yields through poorly understood beneficial soil changes. Recently this was shown clearly in the Valley when wheat following safflower yielded about 10% more than wheat following wheat (Fonteyne and Borbón-Garcia, 2020).

Overall, however, these observations leave little scope for raising FY in the Yaqui Valley through further yield gap closing, suggesting that the main emphasis must be further PY increase. For this purpose, it is worth noting that besides the role of breeding, new agronomy can not only raise efficiency and reduce costs but also lift PY. However, a third factor for the future is that there will be a negative climate change component (warming) in all yields (PY but also equally in FY). These three aspects are now briefly discussed.

Breeding progress in PY has been relatively stable over the last 60 years in absolute terms (Fig. 3a) but the denominator PY has steadily increased (Table 1). However, PY progress has definitely not ceased (stagnated), as some have claimed. The latest bread wheat to reach farmers (CIANO 2018) is in fact reported to outyield Borlaug100 2014 by 7% (Chávez-Villalba et al., 2021). However, the latest durum cultivar (CENEB Oro C-17) appears to only have the PY of Cirno C-08, while offering stronger rust resistance and better semolina pigment content (Chávez-Villalba et al., 2018). The physiology and genetics behind PY progress has often been discussed along with proposed new breeding technologies. The latter are being tested at CIMMYT (e.g., Juliana et al., 2021) to increase efficiency and effectiveness, while genetic engineering for yield, after 20 years of exaggerated promises, appears to have recently delivered one convincing breakthrough for wheat yield (in Argentina, however only under limited water supply, González et al., 2019).

There seems little scope for new PY-lifting agronomy (Fischer, 2020) but crop management has a history of surprises. For example, while no-till permanent beds in the Yaqui only had small wheat yield gains (2–5%), in the long term wheat-maize double cropping experiment of Verhulst et al. (2011), yield increases averaging 10% have been found for wheat after summer fallow, for reasons which are unclear (Fonteyne and Verhulst, 2018). Also deep chiselling combined with controlled traffic (the latter facilitated by permanent beds), and chicken manure for better micronutrition, showed promise (K.D.Sayre pers comm) and merit further research. Once such new agronomy is shown to lift PY profitably, its adoption by farmers becomes yield gap closing and FY rises.

CO_2 increase and warming will undoubtedly continue: other things equal the former should outbalance the latter in wheat yield the Yaqui Valley if Tmin J-M rises at no more than about 0.025 °C/yr. The Tmin increase had been stronger in 2000–19 (0.108 ± 0.050 C°/yr) but much weaker over the whole 60 years study period (0.0167 ± 0.0097 C°/yr). Climate and wheat modelling for the Yaqui Valley by Hernandez-Ochoa et al. (2018) estimates an increase in Tmean of 0.04 °C/yr to 2050, and using an elasticity closer to 0.2 for CO_2 increase effect on yield than the 0.4 as used here, projected irrigated wheat yield with constant technology would fall 5% (relative to 1995). Adaptation through earlier sowing (November rather than December), especially if warmer springs can be reliably forecast, may counter the negative effect of chronic warming (M. Camacho unpublished).

In summary, FY growth at greater than our predicted 1.2% p.a. in the Yaqui Valley looks quite difficult and will probably depend on claimed molecular breakthroughs and other new breeding advances, as well as greater investment in innovative crop management research.

4.4. Is wheat production in the Yaqui Valley sustainable?

Is the intensified wheat cropping system of the Yaqui Valley sustainable intensification? The cropped soils, having evolved under a desert climate, were of inherently low soil organic matter and remain so. Thus fertiliser use has kept pace with yield increase, and there is no clear increase particularly in nitrogen fertilizer use efficiency, being steady at around a quite low value of 25 kg grain/kg N over the last 40 years or so, pointing to moderately high losses. This contrasts with some examples of modern cropping elsewhere (e.g., maize in USA and other examples, Lassaletta et al., 2014). NUE could be substantially improved with changes in timing of N applications to better coincide with crop N uptake, including much less pre-sowing N, and tactical adjustment of later N amounts to meet individual field requirements (Ortiz-Monasterio and Lobell, 2012). However, farmers have been slow to adopt recommended new practices (e.g., N seeker technology) and lack incentive to change.

Biotic threats (disease, weeds, insects) are a special challenge to intensive cropping. However, biocide use on wheat remains modest in the Yaqui Valley yet yield losses are low (probably averaging <5%). Host plant resistance is the first line of defence against diseases, dominated by the rusts (*Puccinia sps*). Variety diversity may seem low but the number, multiplicity, and durability of resistance genes being deployed improves all the time; maintenance breeding is becoming less onerous and more effective (Singh et al., 2014). Monitoring is good and the appearance of leaf rust initially handled by aerial application of fungicide. Weed control has been helped significantly by the switch to seeding in beds and "*siembra sobre humedad*" which permit more mechanical weed control. Herbicide resistance in weeds is inevitable in systems lacking diversity and integrated weed management (IWM) is essential; experience elsewhere suggests effective IWM is possible but needs continuing R, D and E effort and farm management skill (e.g., Preston, 2019). Currently the most important weed threat to wheat production is infestation by bindweed (*Convolvulus arvensis*) but again the solution is integrated management, in particular herbicides and crop competition (Davis et al., 2018). The control of insects (largely aphids) also needs continuing R and D effort: the current reliance on insecticide contrasts with effective IPM 30 years ago (Meisner et al., 1992; Traxler and Byerlee, 1992). As an added insurance against many biotic threats, cropping diversity could be better: in 2017–2019 wheat area was 60% of the total area of annual crops and 65% of cool season ones, and probably at least half of the wheat follows wheat separated only by summer fallow.

The cost- and energy-saving and sustainability benefits of permanent no-till beds with crop residue retention for wheat (and other crops) compared to cultivation, straw incorporation, and fresh bed preparation for each successive crop, has been clearly demonstrated by researchers (Sayre and Moreno Ramos, 1997; Verhulst et al., 2011). However, the yield advantage even after over 20 years of experimental permanent beds has been only a few percent, and adoption remains very limited.

Water availability is an important sustainability issue in irrigated systems. Water use per wheat crop in the Yaqui Valley is not likely to have increased, because laser land levelling and raised beds mean less water wastage. Thus, increased yield has probably lifted water use efficiency (kg/mm) at least 3-fold. Nevertheless, water for agriculture will become scarcer with population growth in Sonora State. Options exist for better managing scarce irrigation water (Schoups et al., 2012), including use of seasonal forecasts of catchment rainfall, canal lining,

[19] Ramírez-Rodrigues et al. (2016) is a first attempt to use seasonal weather forecasting in the Yaqui to reduce risk and improve management decision making; unfortunately, the seasonal forecasts used had poor skill.

and conjunctive use of ground water. However, wheat may not in the long term be able to compete for water with higher-valued crops, especially vegetables and fruits, although the latter have so far failed to meet expectations for a host of reasons (Naylor and Falcon, 2012) and even in 2017–2019 vegetables were only about 10% and fruits 5% of the wheat area.[20]

Sustainability extends beyond the cropped fields and this deserves brief mention here; it is fully explored, including in its social and equity dimensions which will not be discussed here, in Matson (2012) and is receiving increasing attention from civil society groups (McCullough and Matson, 2016). One externality was smoke pollution and associated health problems from stubble fires, but the demise of soybean, and extension and regulation has driven an agronomic solution to this. A bigger external issue is the high level of nitrogen pollution of the atmosphere (N_2O, NH_3), and especially of the drainage waterways (NO_3) leading to the algal blooms in the adjacent Gulf of California and arising largely (estimated at around 85%) from the inefficient use of N fertilizer on wheat (Ahrens et al., 2008). The problem can be substantially countered with improved N management as mentioned. Such environmental considerations feature little in the thinking of the large credit union input suppliers whose approach to wheat inputs is still dominated by profitability (McCullough and Matson, 2016). This reflects a general challenge with irrigated cropping in the developing world, with N fertilizer often still subsidized (e.g., China, Indo-Gangetic Plain), and again demands greater attention from research, independent extensionists, policy-makers, and farm mangers themselves, a common theme as we look to more sustainable cropping. Finally for externalities, we have greenhouse gas emissions, best expressed as yield-scaled emissions (kg CO_2 equivalent per kg wheat produced). High yield cropping, as in the Yaqui Valley, performs favourably on this basis (Fischer et al., 2014), but improving N use efficiency and specifically reducing N_2O emissions along the lines suggested would notably improve the situation.

4.5. Conclusion

On balance wheat is likely to remain king for another 20-year period in the Yaqui Valley, especially from PY increase through breeding, but yield gap closing is becoming limited. FY growth as high as today's 1.47% p.a. seems unlikely, and 1.2% p.a. is estimated for the next 20 years in the absence of new technologies. This FY growth prospect is now below the projected global demand growth for wheat. Yield gap closing elsewhere in the developing world, for which fortunately, there is still significant scope (Fischer, 2019), will become even more urgent. Biophysical sustainability of the Valley wheat cropping system is likely to improve through better N fertiliser management, as energy price, and net zero CO_2 and environmental signals begin to be felt. Improvements are also possible through greater cropping diversity, integrated management of biotic threats, and acceptance of no-till, residue retention and controlled traffic. With continuing or preferably greater R, D and E efforts, and informed farm management and policy, the Valley should remain an important beacon for sustainable intensification in irrigated wheat cropping.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[20] Cool season maize (largely feed grain) was the recent outstanding performer, rising to 30% of the wheat area in 2017–2019; no other crop exceeded 10% of the wheat area.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2022.108528.

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