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Conservation agriculture enhances maize yields and profitability in Mexico's semi-arid highlands

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Rainfed agriculture in semi-arid regions is affected by variable rainfall patterns, resulting in low yields under conventional farming systems. To address this issue, cropping systems based on conservation agriculture were evaluated in 2 field experiments on 17 farmers' fields in the semi-arid highlands of Queretaro, Mexico, from 2013 to 2020, to assess yields and profitability. Monocropped maize (*Zea mays* L.) under conventional tillage was compared to growing maize on permanent beds with soil mulch, either monocropped or in rotation with triticale (*X Triticum Secale* Wittmack), oats (*Avena sativa* L.), or common beans (*Phaseolus vulgaris* L.). In the San Juan del Rio field experiment, maize yields on permanent beds averaged from 2,475 to 3,517 kg ha^{-1} over five years, exceeding 70% the yields under conventional tillage. In the Cadereyta field experiment, 4-year average maize yields on permanent beds ranged from 979 to 1,382 kg ha^{-1} with no significant difference to those under conventional tillage. In farmers' fields, maize on permanent beds yielded an average of 3,717 kg ha^{-1}, 70% higher than with conventional tillage. The most profitable system was permanent beds with a maize-bean rotation in field experiments and with maize monocropping in farmers' fields. Overall, conservation agriculture can improve maize yields and profitability in Central Mexico's semi-arid highlands.

Keywords Conservation agriculture, Crop rotation, Permanent beds

Climate change has altered hydrological patterns worldwide, reducing crop yields under rainfed agriculture and particularly in semi-arid areas. These areas, characterized by a negative annual water balance, cover approximately 45% of the Earth's land surface[1,2], . Rainfed crops are susceptible to both seasonal variations in precipitation and, especially, the intensity and duration of rainfall events. Semi-arid cropping systems need to be adapted to unpredictable weather conditions and recurrent extremes, such as dry spells, all of which are becoming more frequent[1]. To address these challenges, conservation agriculture (CA) — a system based on minimum soil movement, permanent soil cover, and crop diversification — has been proposed. Unlike conventional production methods that typically involve tillage, monoculture, and residue grazing, CA offers a sustainable alternative for environments with limited water resources[3,4].

Each component of CA has a potential benefit when compared with conventional agriculture[5], but the maximum benefits of CA are typically realized when all CA practices are fully implemented together[4]. Worldwide there has been widespread adoption of reduced tillage systems with varying degrees of application of the other CA principles; nonetheless, the reduction of tillage as an isolated practice often leads to reduced yields[3,6,7]. Applying all CA components can be challenging for farmers such as those in semi-arid zones, who may lack economically viable crops for diversification, and the multiple uses and economic value of crop residues make it difficult for farmers to use them simply as a soil cover, in many settings[8–10]. Crop rotations in contrast are beneficial even in conventional tillage systems[4,11]. To assess the profitability of cropping systems, all crops must be considered; their combined profitability drives decisions to adopt particular rotations[12].

The benefits of CA typically accrue in the medium and long term[8], so to foster adoption by the smallholder farmers who predominate in semi-arid zones, CA must be combined with other management practices that maximize their effects and provide short- and long-term benefits[13]. There is evidence of yield increases with conservation agriculture based cropping systems in the semi-arid regions[4], including the semi-arid, subtropical highlands of Central Mexico[14]. However, considering that CA effects are regionally and even site-dependent, CA systems must be tested and refined under local conditions and adapted to local farmers' circumstances and needs[3,8].

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In this context, the International Maize and Wheat Improvement Center (CIMMYT) and its partners have established a network of adaptive trials and demonstration plots across Mexico, encompassing the semi-arid region in the central Mexican highlands[15,16]. There, smallholder farmers practice rainfed agriculture to produce maize and beans as food crops and for livestock feed and forage. The yields are low compared to the national average[17], due to the limited rainfall and because farming often takes place on steep slopes in highly-degraded soils, aggravated by limited agronomic management and inadequate agricultural practices such as monocropping and overgrazing.

The primary objective of this study is to evaluate the productivity and profitability of maize and associated crops under conservation agriculture-based cropping systems compared to conventional tillage. To validate the hypothesis that conservation agriculture enhances crop productivity and profitability in a semi-arid region, we conducted field experiments in the state of Querétaro, Mexico in the municipalities of San Juan del Río from 2014 to 2018 and Cadereyta from 2015 to 2019. Additionally, we analyzed data collected from 2013 to 2020 from farmers' fields within the CIMMYT network in this region.

Materials and methods

Site description

The field experiments were established under rainfed conditions in the semi-arid region of the state of Queretaro in Central Mexico (Fig. 1). In this region, the average temperature is 17 °C and annual precipitation is 550 mm; while during the growing season, average precipitation is 392 mm[18]. One experiment was conducted in the community of Santa Rosa Xajay, San Juan del Rio municipality (N 20,450 N, W 99,905), which lies at 1972 m above sea level (masl). The soil was a Phaeozem with a sandy loam texture, with a depth of less than 40 cm and a slope of 3%. We conducted another experiment (Cadereyta) in the San Martin Florida community, Cadereyta de Montes municipality (N 20.749, W 99.823), at 2000 masl. The soil was a clay loam Vertisol, with a depth greater than 1 m and a slope of less than 1%.

To compare the results of the experiments above with on-farm results, we selected data from 29 site-years of farmers' fields under rainfed conditions and this had a side-by-side comparison of conventional tillage (CT) and CA, in municipalities in semi-arid zones of Querétaro (Fig. 1), with precipitation during the growing season ranging from 400 to 500 mm[19]. Farmers' fields were part of CIMMYT's work with innovation on the agri-food system through the hub model[15].

San Juan Del Rio

The experiment ran from 2013 to 2019, but there was an extreme drought that resulted in crop failure the last year, so the yield was reported until 2018. In 2013 all treatments were sown with conventional tillage, to facilitate the formation of beds and marking of contour lines to reduce erosion and improve water distribution

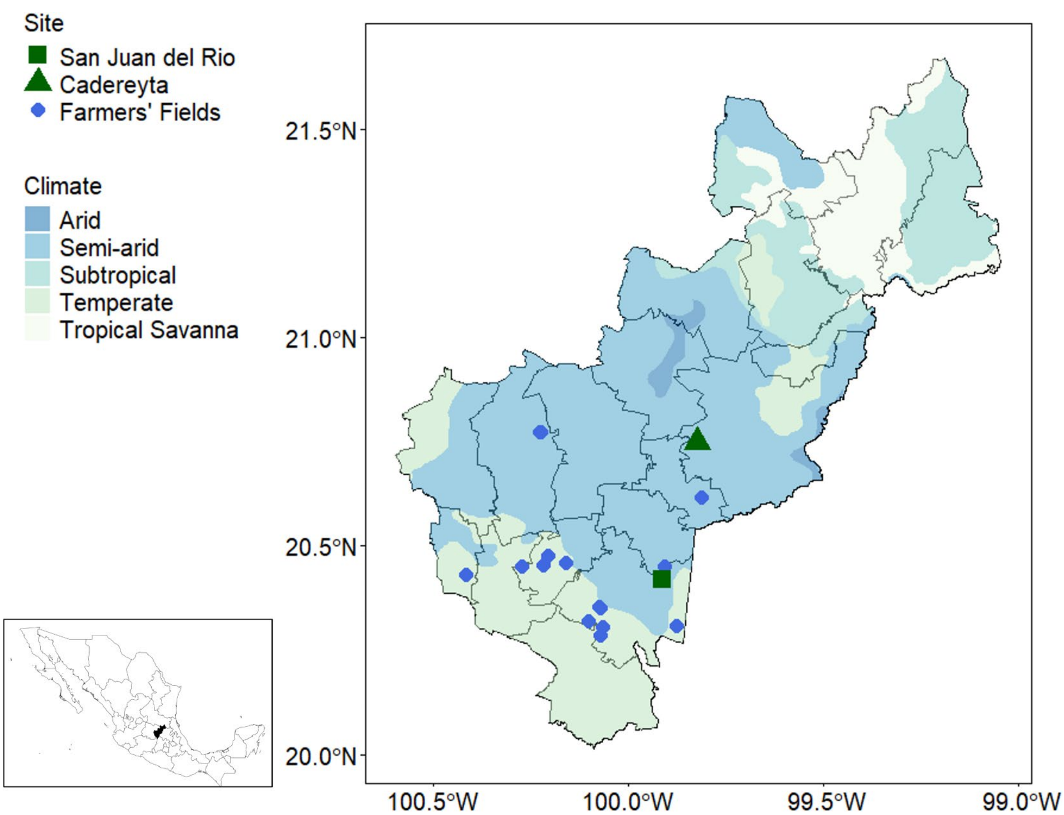

Fig. 1. Location of the field experiments and municipalities of farmers' fields, state of Queretaro, Mexico.

Treatment	Tillage	Residue management	Crop rotation
CT, MM	Conventional tillage	Removal	Maize monocropping
PWB, MM	Permanent wide beds	Leave	Maize monocropping
PWB, MO	Permanent wide beds	Leave	Maize - oats rotation
PWB, MT	Permanent wide beds	Leave	Maize - triticale rotation
PWB, MB	Permanent wide beds	Leave	Maize - bean rotation

Table 1. Treatments, San Juan Del Rio field experiments, 2013–2019.

Year	NPK rate	Precipitation (mm)
2014	75-18-5	-*
2015	100-18-5	330
2016	107-46-30	345
2017	89-45-22	329
2018	55-22-11	319
2019	40-30-15	70

Table 2. Fertilization rates and precipitation during the crop cycle, San Juan Del Rio experiments. *Data not available.

across the slope. From the second year onwards, tillage was carried out according to the treatments (Table 1). The experimental design was randomized complete blocks, with two repetitions, on plots measuring 84 × 6 m (Supplementary Fig. 1). In this study, data from five contrasting treatments were analyzed. The control treatment (CT, MM) consisted of maize monocropping with all the stubble removed to simulate the grazing that is common in the area. Soils were disk plowed to a depth of 30 cm followed by forming 1.5 m wide beds, each year. The other treatments were sown on wide permanent beds, where the top of the raised beds was not tilled and furrows were reformed once a year[20]. Permanent beds were planted with maize (*Zea mays* L.), either monocropped (PWB, MM) or in rotation with oats (*Avena sativa* L.) (PWB, MO), triticale (x Triticosecale) (PWB, MT), or beans (*Phaseolus vulgaris* L.) (PWB, MB), for rotational treatments, each crop was sown each year in separate plots. For permanent beds, maize stubble was rolled and left on the soil surface, forage crops were cut at 10 cm above soil level for harvest, and for beans the whole plant was removed at harvest, as they are commonly threshed outside of the field.

Each crop was dry sown each year at the beginning of the rainy season in early June. We sowed two rows of maize or beans on wide beds separated by 0.75 m; for triticale and oats, four rows were sown per bed. From 2013 to 2017, we used the drought-tolerant maize variety Cafime[21], while in 2018 we grew the commercial hybrid CRM28 (Bayer, Mexico), which had shown superior yields and stability in 5 years of continuous experiments[22]. Seed rates for Cafime were 66,500 to 70,000 seeds ha^{-1} and for CRM28 71,500 seeds ha^{-1}. We grew the Pinto Saltillo bean, sown at a rate of 40 kg ha^{-1}. Oat varieties were Karma and Turquesa, sown at 100–150 kg ha^{-1}.

For maize, agronomic management was similar for all treatments. For weeds, we selectively applied herbicide early in crop development except for 2018, where glyphosate was applied to all permanent beds. We used pheromone traps to control fall armyworm (*Spodoptera frugiperda*) and sticky traps for leafhopper (Hemiptera, Cicadellidae) or whitefly (Hemiptera, Aleyrodidae). Where pest damage reached economic thresholds, we applied insecticides to the damaged crop. Fertilization was the same for all crops each year: two applications at sowing with 50% nitrogen and all phosphorus and potassium and the remaining nitrogen 30–45 days after crop emergence. The sources for NPK fertilizers were ammonium sulfate, urea, diammonium phosphate, and potassium chloride. No previous research was available on which to base fertilizer rates, so we applied different rates each year based on expected yield (Table 2). Precipitation in the growing season was measured with a rain gauge.

Cadereyta

We began this trial in 2015, first tilling the entire field (Table 3). The experimental design was randomized complete blocks with two repetitions on plots of 100 × 6 m (Supplementary Fig. 1. In this study, data from four contrasting treatments were analyzed. The conventional tillage in treatment CT, MM comprised disk plowing to a depth of 30 cm, planting on the flat, and the maize residue was removed. Permanent beds (1.6 m wide) were reformed each year and used to grow monocropped maize (PWB, MM) or maize in rotation with oats (PWB, MO) or beans (PWB, MB). On permanent beds we kept maize residues as a soil cover, removed whole bean plants at harvest, and cut oat stems at 10 cm height. In rotation treatments, each crop was sown each year on separate plots after the outset of the rainy season. Plant spacing and seed rate were the same as in the San Juan del Rio experiment, and we used the maize variety Cafime, the bean variety Pinto Saltillo, and the fodder oat variety Turquesa. Weed, pest, and fertilizer management were similar to those in the San Juan del Rio experiment (see Table 4, for NPK rates).

Treatment	Tillage	Residue management	Crop rotation
CT, MM	Conventional tillage	Removal	Maize monocropping
PWB, MM	Permanent wide beds	Leave	Maize monocropping
PWB, MO	Permanent wide beds	Leave	Maize - oats rotation
PWB, MB	Permanent wide beds	Leave	Maize - bean rotation

Table 3. Treatments, cadereyta experiments, 2015–2019.

Year	NPK rate	Precipitation (mm)
2016	105-30-15	192
2017	97-60-30	181
2018	43-21-11	449
2019	10-21-10	-*

Table 4. Fertilization rates and precipitation during the crop cycle, Cadereyta. *Data not available.

Farmer field data

We chose 17 farm fields where conventional tillage was compared to permanent beds with maize monocropping (12) or maize-bean rotation (5 sites) during 2013 to 2020 — a total of 29 site-years providing data on farmer-managed side-by-side comparisons in single fields. In the conventional tillage treatment (CT, MM), farmers plowed using either a disc harrow or disc plow, or both. On permanent beds, farmers reshaped the furrows as needed. Maize was grown either as a monocrop (PB, MM) or in rotation with beans (PB, MB). Crop management was the same for both treatments and followed the same strategy as the experiments in more controlled conditions, as defined by the farmer and the farm advisor. Precipitation data were obtained from Daymet[19].

Data collection and statistical analyses

In the two field experiments, the central area of each plot was harvested manually (1.5–1.6 m x 15 m), threshed by hand, the moisture content determined using a moisture meter (John Deere, Moline IL, USA), and the content adjusted to 14% for maize and 12% for beans. For oats and triticale, green fodder yield was estimated. The same method was employed for farmers' fields, but the harvested area was variable by field.

Profitability was calculated as the net income, from the sale of the harvested product at the local market, minus production costs. Production costs were estimated using the prices that were current each year from local suppliers for each operation and input. We did not consider opportunity costs or residue income, since residues are normally grazed and not sold. For systems with crop rotation, we considered the average production costs of growing both maize and the rotational crop as well as the average net incomes for both crops. In farmers' fields, only one crop was grown each year.

Statistical analysis was performed in R 4.3.1 (R core team, Vienna, Austria). The effect of treatments on yield and profit was analyzed using a linear mixed model for analysis of variance.

For data from field experiments, the model used was:

$$\mathrm{Y_{ijk} = m + T_i + R_j + S_k + e_{ijk}}.$$

Where Y_{ijk} is the variable response in the ith treatment and the the jth repetition under the kth year, m is the overall mean, T_i is the effect of ith treatment, R_j is the effect of ith repetition, S_k is the effect of kth year and e_{ijk} is the error associated with the ith treatment, the jth repetition and the kth year.

For data from farmers' fields, the model used was:

$$\mathrm{Y_{ijk} = m + T_i + M(F)_j + S_k + e_{ijk}}.$$

Where Y_{ijk} is the variable response in the ith treatment and the the jth municipality under the kth year, m is the overall mean, T_i is the effect of ith treatment, $M(F)_j$ is the effect of ith municipality nested on field, S_k is the effect of kth year and e_{ijk} is the error associated with the ith treatment, the jth municipality and the kth year.

Normality and homogeneity of variance were tested on the residuals of the models. The residuals were normally distributed and homoscedastic. Post-hoc analysis was performed to determine differences between treatments using the HSD test with significance at $\alpha = 0.05$.

Results

San Juan Del Rio

Maize yields ranged from 957 to 6,220 kg ha^{-1} over years and treatments (Fig. 2), with higher yields in 2018, when a maize hybrid was grown. The yield of monocropped maize on permanent beds was not statistically different from that for maize under conventional tillage (Table 5). Permanent beds with crop rotations gave significantly higher average maize yields than conventional tillage but — except for the maize-oats rotation — not than monocropped maize on permanent beds. The average yield of the treatments in permanent beds with

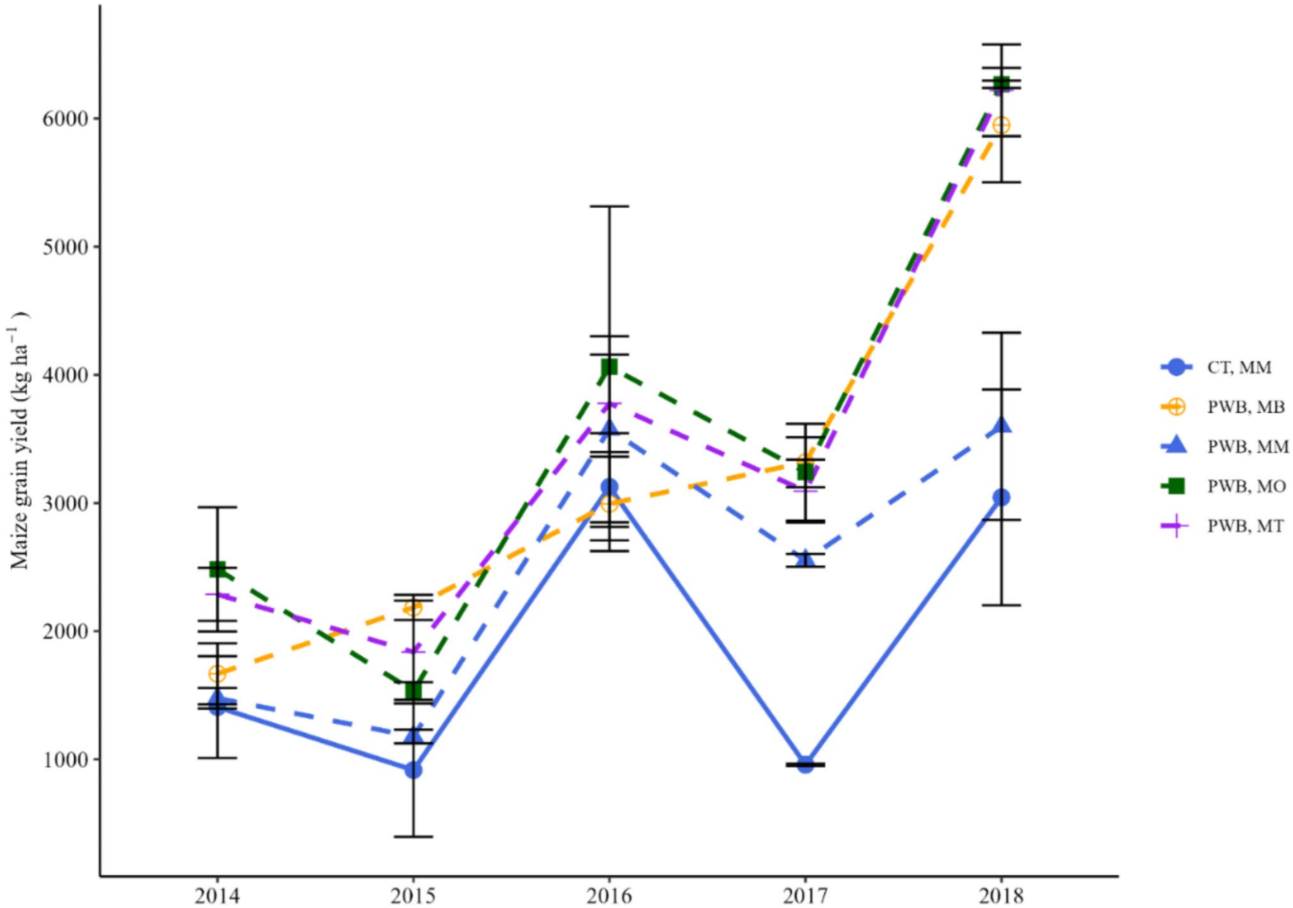

Fig. 2. Effect of cropping system on maize yield in San Juan del Rio field experiments, 2014-18. The error bars represent the standard error of the mean. In 2019 there was a complete crop failure due to drought. Abbreviations: CT = Conventional tillage, PWB = Permanent wide beds, MM = Maize monocropping, MB = Maize-bean rotation, MO = Maize-oats rotation and MT = Maize-Triticale rotation.

Treatment	Yield (± Standard Error)	Profit (± Standard Error)
CT, MM	1,890 (371.9) c	-2,299 (1214.9) b
PWB, MM	2,475 (372.1) bc	441 (999.9) a
PWB, MO	3,517 (575.4) a	956 (929.8) a
PWB, MT	3,442 (525.0) ab	385 (725.6) ab
PWB, MB	3,222 (504.1) ab	1,914 (821.7) a

Table 5. Mean maize yields (kg ha^{-1}) and profits (MXN ha^{-1}), under different cropping systems, in San Juan Del Rio field experiments, 2014-18. Means followed by the same letter are not significantly different using the HSD test, ($\alpha = 0.05$). Abbreviations: CT = conventional tillage, PWB = permanent wide beds, MM = Maize monocropping, MB = maize-bean rotation, and MO = maize-oats rotation.

crop rotations was 3,339 kg ha^{-1}; more than 30% above the yield of monocropping on permanent beds and 70% higher than for conventional tillage.

For fresh biomass, fodder oat yields ranged from 1,330 to 5,670 kg ha^{-1} and fodder triticale yields from 2,401 to 4,970 kg ha^{-1} (0.0 kg ha^{-1} in 2018 due to drought-occasioned crop failure). Bean grain yield ranged from 94 to 1,088 kg ha^{-1} (Supplementary Fig. 1).

The production costs of maize monocropping under conventional tillage were 8% higher than for monocropped maize on permanent beds, due to tillage operations. Monocropped maize cost between 4 and 17% more than crop rotations, due the costs of seed, pesticides, and harvesting (Supplementary Table 1). The net profit for monocropped maize using conventional tillage was negative and statistically different from that for maize cropping under CA, except for the maize-triticale rotation. For monocropped maize on permanent beds and the triticale-maize rotation, profits just passed the break-even point. The highest profits were obtained from the maize-bean rotation. There were no significant differences in profits among CA-based treatments (Table 5).

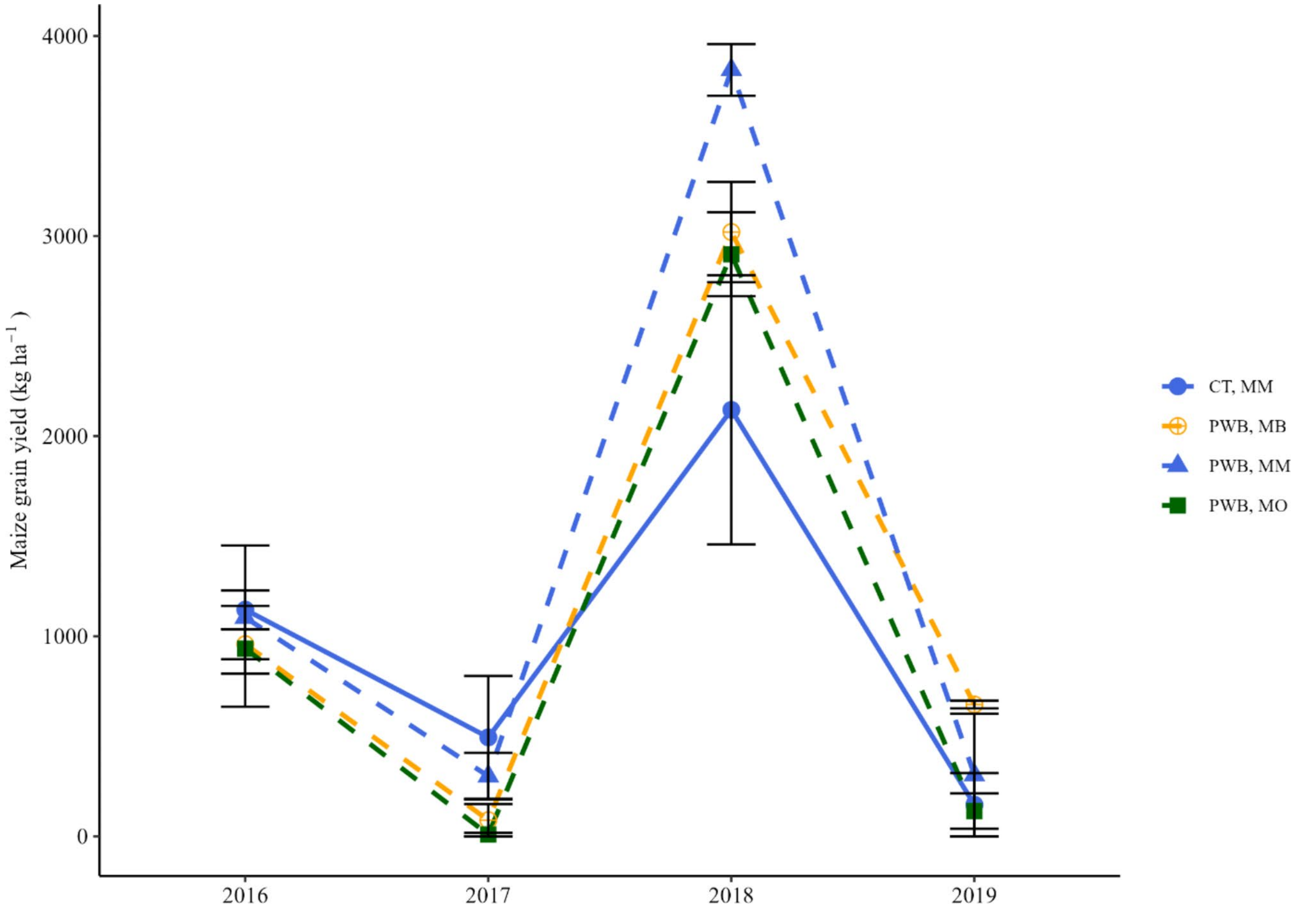

Fig. 3. Effect of cropping system on maize yield in the Cadereyta field experiments. The error bars represent the standard error of the mean. Abbreviations: CT = Conventional tillage, PWB = Permanent wide beds, MM = Maize monocropping, MB = Maize-bean rotation and MO = Maize-oats rotation.

Treatment	Yield (± Standard Error)	Profit (± Standard Error)
CT, MM	979 (323.7) a	-4,806 (1040.1) b
PWB, MM	1,382 (552.0) a	-2,664 (1778.5) ab
PWB, MO	995 (444.4) a	-4,125 (815.0) ab
PWB, MB	1,179 (422.1) a	-1,275 (1847.1) a

Table 6. Mean maize yields (kg ha^{-1}) and profits (MXN ha^{-1}), under different cropping systems in the Cadereyta field experiment, 2015-19. Means followed by the same letter are not significantly different using the HSD test, (α = 0.05). Abbreviations: CT = conventional tillage, PWB = permanent wide beds, MM = Maize monocropping, MB = maize-bean rotation and MO = maize-oats rotation.

Cadereyta

Average yields among treatments in Cadereyta were similar and no significant differences observed in any year. Yields within treatments varied greatly each year (Fig. 3). Monocropped maize on permanent beds gave the highest yield, followed by maize in rotation with beans, monocropped maize under conventional tillage, and maize in rotation with oats (Table 6). Bean yields averaged 1,569 kg ha^{-1} in 2018 and 162 kg ha^{-1} in 2017. Fodder oat yields averaged 6,618 kg ha^{-1} in 2018 and the lowest average yield for this crop was 2,916 kg ha^{-1} in 2019 (Supplementary Fig. 2).

Production costs for maize monocropping under conventional tillage were 6% higher than for monocropped maize on permanent beds, due to tillage operations. Monocropped maize was 1.5% cheaper to grow than the maize-bean rotation, due to the cost of manually harvesting beans. The lowest production cost was for the maize-oats rotation (Supplementary Table 1). The net profit for all treatments was negative. The maize-bean rotation had a significantly lower net loss than conventional tillage (Table 4), because of beans' high market value.

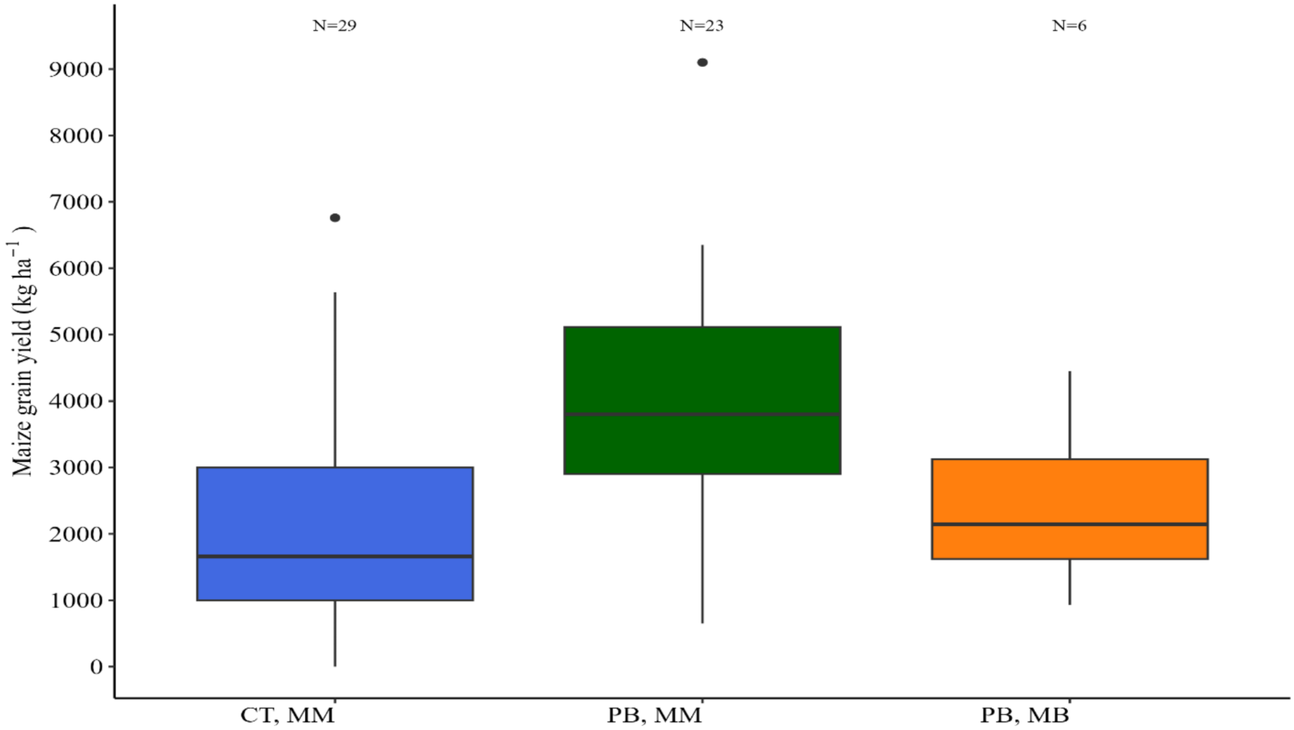

Fig. 4. Effect of cropping systems on maize yield in farmers' fields, Queretaro, Mexico. Abbreviations: CT = Conventional tillage, PWB = Permanent wide beds, MM = Maize monocropping, MB = Maize-bean rotation and MO = Maize-oats rotation.

System management	Yield (± Standard Error)	Profit (± Standard Error)
CT, MM	2086 (303.3) b	720 (828.8) b
PB, MM	3913 (401.9) a	4896 (1295.5) a
PB, MB	2428 (527.4) a	4267 (2177.3) ab

Table 7. Mean maize yield (kg ha^{-1}) and profit (MXN ha^{-1}), under different cropping systems, in farmers' fields. Means followed by the same letter are not significantly different using the HSD test, (α = 0.05). Abbreviations: abbreviations: CT = conventional tillage, PB = Permanent beds, MM = Maize monocropping and MB = maize-bean rotation.

Trials in farmers' fields
Maize yields in farmers' fields ranged from 0 to 9,000 kg ha^{-1} (Fig. 4 and Supplementary Fig. 3). Cropping with conventional tillage provided the lowest average yield (2,086 kg ha^{-1}) and was statistically different from the average yield for cropping on permanent beds (Table 7).The highest average yield of 3,913 kg ha^{-1} was achieved with monocropped maize on permanent beds, followed by maize on permanent beds with rotations (2,428 kg ha^{-1}). There were no significant differences observed between these two systems. Growing season rainfall ranged from 250 to 500 mm among sites and years, but the yield difference between permanent beds and conventional tillage was not correlated with rainfall (Fig. 5).

Production costs were lower for conventional tillage systems than for permanent beds (Supplementary Table 1). The highest profit was obtained from monocropped maize on permanent beds; significantly above that for moncropped maize under conventional tillage and was similar to the maize-bean rotation.

Discussion
We recorded on average less than 400 mm of precipitation in San Juan del Rio, with high seasonal variability, including an absence of rain that resulted in total crop failure in 2019. In Cadereyta, the maximum precipitation recorded was about 450 mm, but there was a difference of 250% in total precipitation between the driest and wettest years. Maize needs more than 500 mm of seasonal rain for a productive crop[23], so conditions in semi-arid central Mexico would be considered unsuitable for maize cultivation by most farmers. Given that farmers will continue to grow maize under such precarious conditions, they need improved cropping systems to ensure their food security and livelihoods.

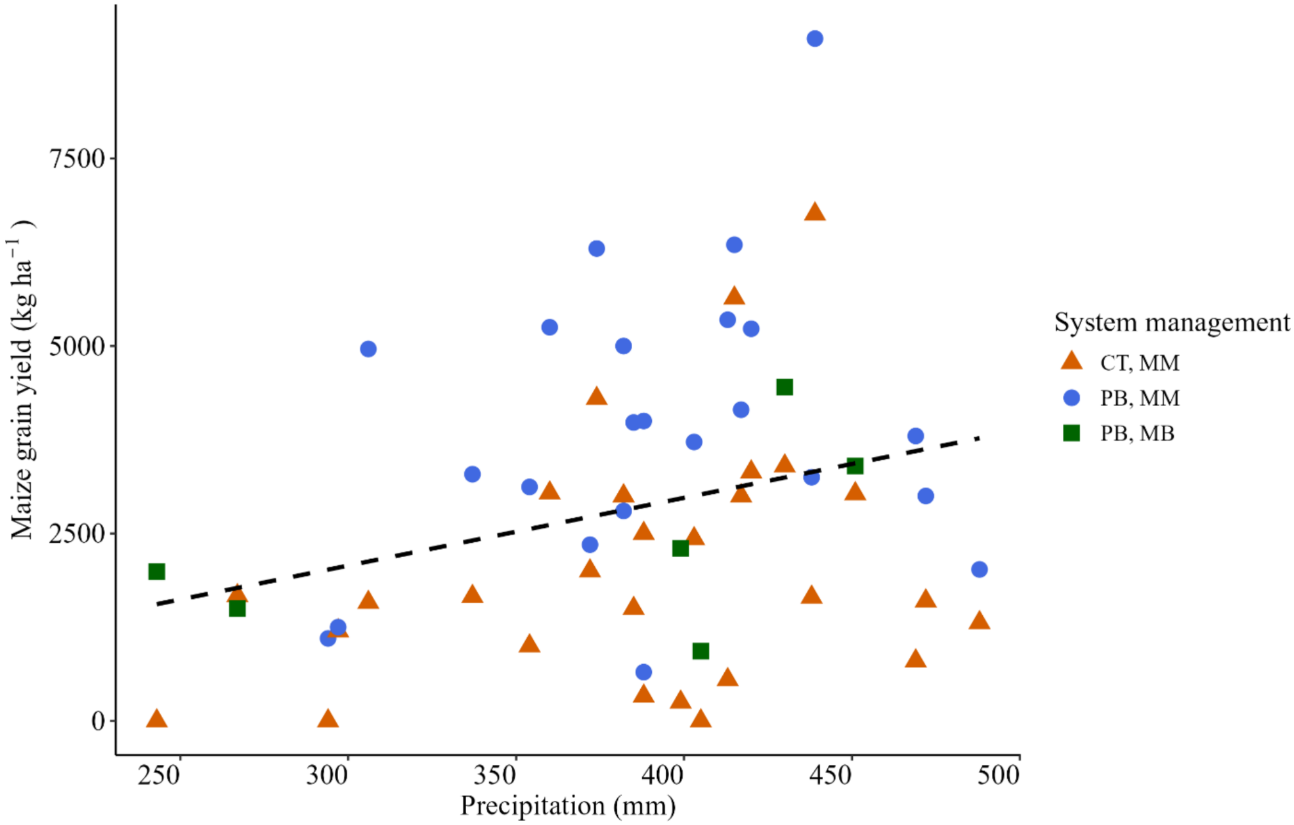

Fig. 5. Relationship between precipitation and yield under different cropping systems in farmers' fields, Queretaro, Mexico. ($R2 = 0.064$, $n = 66$, $p < 0.031$). Abbreviations: PB = Permanent beds, MM = Maize monocropping, MB = Maize-bean rotation.

The average yield of monocropped maize on permanent beds was approximately 35% higher than that under conventional tillage in the field experiments and 70% higher in farmers' fields, although this difference was statistically significant only in the latter. Similar findings have been reported in previous research, where maize monocropping under conservation agriculture performed similar to conventional tillage[4,24,25].

Conservation agriculture significantly increases rainfed maize productivity in dry regions by improving soil properties such as organic matter, stable aggregates, water infiltration, and soil microbial biomass[4,6,8,26]. Previous studies, that include San Juan del Rio and Cadereyta field experiments, have reported soil quality parameters and compared them between conventional tillage and permanent beds[8,27]. The soil quality parameters showed only marginal improvements. For example, conservation agriculture had a positive impact on soil bulk density and pH but, after five years, did not significantly affect soil organic matter content. The effect of conservation agriculture on soil organic carbon is generally greater at sites with higher precipitation and biomass production, so it may take a long time to observe an increase in soil organic matter in semi-arid conditions[26,28]. Under the conditions of our study, no major change in soil organic matter content was to be expected.

The maize-oats rotation had a higher maize yield than maize monocropping in San Juan del Rio, but the maize-bean rotation provided maize yields comparable to those of maize monocropping at both experimental sites and in farmers' fields. Generally, maize-legume rotation boost maize yields, but the effects tend to be site-dependent[4,24,29], with crop rotation having higher productivity in poorer environments[30].Permanent beds and soil mulch can provide moisture in short dry periods, improving conditions for a maize crop[31], but the maize-bean rotation, where bean plants are completely removed at harvest and thus leave little or no residue for soil mulching. The physical effects of soil mulch — intercepting raindrops under heavy rainfall and reducing evaporation — contribute significantly to rainwater use efficiency[4,31]. These results are consistent with previous research findings in Southern Africa, where mulching has been identified as the most promising method for increasing maize yields in dryland regions[4]. To address residue scarcities, future research could evaluate whether rotation crops that produce abundant biomass might be better than beans[32].

No significant differences were observed among treatments in the Cadereyta field experiment, even though conservation agriculture-based cropping systems showed higher average yields and profitability. This site had low precipitation in three of the four years of the study, and the combination of substantial variation and only two replications made it difficult to achieve statistical significance. Strategies with the potential to improve water availability are necessary to complement conservation agriculture, such as the contour lines we built in San Juan del Rio[4,11]. In 2018, at San Juan del Río, the use of the commercial hybrid CRM-28 — which has a longer crop cycle than the variety Cafime —resulted in greater differences in maize yields across cropping systems, attributable to improvements in growing conditions in permanent beds with crop rotations where the use of late-maturing varieties can improve yield when growing conditions improve[2].

The profitability of conservation agriculture systems in smallholder farming depends on several factors and is often difficult to measure. Crop failures are frequent in semi-arid regions, so farmers use few inputs due to the high risk and low yield potential[2]. Accordingly, actual production costs in semi-arid farming can be as much as 50% less than reported here, but we followed what were considered good agronomic practices, fertilizing according to recommendations and with weed management, both of which are important to obtain the maximum benefits of conservation agriculture[13].

Under our experimental conditions, the income of the control treatment was always low or negative, but farmers normally exclude their labor from their economic assessments and thus would not necessarily concur with our analysis. Nevertheless, conservation agriculture was more profitable than conventional tillage both in the field experiments and in farmers' fields. Permanent beds with maize monocropping in Cadereyta and maize-oats rotation in San Juan del Rio had the highest maize yield, but the higher market price for beans resulted in the maize-bean rotation being more profitable at both sites. In farmers' fields, permanent beds with monocropped maize or rotations gave similar maize yields and profitability.

Inputs such as fertilizers and herbicides increase costs and farmers will judge whether an expected increase in crop yields justifies these expenses, since low incomes were reported at all sites and the costs of weed control with herbicides are not necessarily compensated by avoiding yield losses. Further research for similar low-yield conditions should focus on non-monetary inputs to increase profitability[33], as well as the adequate integration of raising livestock, a common practice in these regions. We did not consider possible income generated by crop residues, in the conventional tillage, because free-ranging grazing is the common practice and farmers are not compensated for this. In other semi-arid regions, crop residues can represent nearly 40% of the gross margin of maize production in dry seasons if sold[9], so the profit could be as high as that of the maize-bean cropping system on permanent beds and conservation agriculture could be less attractive for these farmers.

The production systems we evaluated in our field experiments could benefit farmers in semi-arid regions, but their adoption would require a fundamental shift in farming practices and address or alter conventions such as free grazing. Government agencies and non-governmental organizations can play a crucial role in supporting a transition from conventional to more sustainable farming practices such as conservation agriculture, providing technical assistance, resources, and incentives. Additionally, they can help develop and enforce regulations or alternative management strategies for livestock[9].

Conclusions

The conservation agriculture-based cropping systems we tested resulted in an average maize yield advantage of approximately 1,200 kg ha^{-1} over conventional tillage, despite variable rainfall patterns and agronomic management. In San Juan del Río, the maize-forage crop rotation grown on permanent beds afforded higher yields of maize than the maize monoculture on permanent beds or the maize-bean rotation. In drier conditions, such as those of Cadereyta, using crop residues as a soil cover for a maize monoculture gave the highest maize yields, attributable to the mulch's improved water capture and conservation. At both experimental sites, permanent beds with a maize-bean rotation proved the most profitable system. In farmers' fields, permanent beds gave higher maize yields and profitability than conventional tillage. In semi-arid Central Mexico, conservation agriculture cropping systems increased maize yields and system profitability.

Data availability

The data are openly available in Dataverse at: https://hdl.handle.net/11529/10549071.

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Author contributions
N.V. and S.F. contributed to the conception and design of the study. J.M.R.C. and M.A.U.G. carried out the fieldwork and data collection. A.S.T. and O.G.M.G. conducted data analyses. A.S.T. wrote the first draft of the manuscript. N.V. and S.F. supervised the project, and reviewed, and edited the draft. All authors contributed to the revision of the manuscript and read and approved the submitted version.

Declarations

Competing interests
The authors declare no competing interests.

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