Does residue cover lead to greater frost damage in barley under conservation agriculture?

Simon Fonteyne[1], Juan Manuel Rojas Cruz[2], Avelino Espinosa Solorio[2], Nora Honsdorf[3], Abel Saldivia Tejeda[1], Ouorou Ganni Mariel Guera[1], Nele Verhulst[1]

[1] International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico
[2] Sustentabilidad Agropecuaria de Querétaro (SAQ), Querétaro, Mexico
[3] Christian-Albrechts-Universität zu Kiel, Kiel, Germany

Abstract

Farmers reported increased frost damage in barley (*Hordeum vulgare*) sown in conservation agriculture in the Mexican Bajío region during the autumn-winter season. To determine whether this effect is real and whether it reduced crop yield under conservation agriculture, we performed two field experiments and gathered observational data from other experiments and farmers' fields. Although more frost damage can sometimes indeed be observed in wheat and barley sown in permanent beds with stubble cover, the data indicate that the plants recover from this damage and that it does not affect yield. Frost damage should not be considered an impediment to adoption of conservation agriculture in the crops grown in the autumn-winter season in the Mexican Bajío.

Introduction

Conservation agriculture (CA), the production system based on minimum tillage, permanent soil cover and crop diversification has been shown to have many potential benefits compared to conventional agriculture, such as reduced production costs, water use and greenhouse gas emissions, as well as improved yields and soil health (Dendooven *et al.*, 2012; Follett *et al.*, 2005; Fonteyne *et al.*, 2021b, 2021a; Verhulst *et al.*, 2011). Because of these benefits CA has been widely promoted with farmers, including in the Mexican Bajío region (Martinez-Cruz *et al.*, 2019; Monjardino *et al.*, 2021; Van den Broeck *et al.*, 2013).

The Bajío region is one of the main grain producing regions of Mexico, most farmers with access to irrigation sow maize (*Zea mays* L.) during the spring-summer cycle (May-December) and sow small grains cereal (wheat or barley) in the autumn-winter cycle (December-May). While the summer crops are mostly rainfed, winter crops rely completely on irrigation, mostly furrow irrigation. In the region, low temperatures occur regularly during the winter growing season, and frost events can occur, though they are infrequent and do not occur every year. Low temperatures are necessary for wheat and barley to induce tillering and therefore to obtain high yields (Fischer *et al.*, 2022), however frost and low temperatures can also cause damage to plants, which can have an impact on yield (Fonteyne *et al.*, 2016).

Agriculture in the region is highly productive, leading to the production of large quantities of crop residues. Residues as soil cover have many beneficial effects in CA systems. However, if quantities become too large technical problems may arise, e.g., at sowing. Residues also alter the microclimate and can lead to slower warming of the soil. In the Bajío, where frost occasionally occurs one of the concerns mentioned by farmers about switching from conventional practices to CA is whether frost damage is more likely to occur under the latter management technique.

To evaluate whether higher levels of residues lead to higher frost damage in small grain cereals in the Bajío we performed three experiments: 1) A field experiment on the effect of residue levels on barley yield in the Bajío in San Juan del Rio, Queretaro 2) A field experiment in Metepec, Mexico State, located in the highlands of Mexico, where frost is certain to occur and 3) Analysis of yield data from field experiments and on farm side-by-side comparisons in Bajío and the Pacific Northwest. The objective of the report was to bring together observations and first experimental data to determine whether frost is a problem in CA in the region and whether more research on avoiding frost damage in CA is needed.

Materials and Methods

Experiment descriptions

Experiment 1: The San Juan del Rio III research platform

The experiment was located in a region where frost often occurs during the winter season, San Juan del Rio in the Bajío part of Queretaro state. The objective of this experiment was to answer two research questions:

1) Is barley yield lower with reduced tillage?
2) When using reduced tillage, is yield lower when residues are left in the field?

The experiment was performed in the San Juan del Rio III research platform, which forms part of the innovation hub network CIMMYT operates in Mexico (Gardeazabal *et al.*, 2023; Govaerts *et al.*, 2021). The trial was located in a farmer's field in El Organal, San Juan del Rio, Querétaro (N20.46592, W100.09205). The soil is classified as Vertisol and is irrigated using water from a nearby dam. The region has a dry temperate climate with an annual mean temperature of 16.5°C and a mean annual rainfall of 572 mm (Supplementary figure 1). In the 29 years (1997-2016) that meteorological data are available, there were 550 events where the temperature went below 2 °C and 95 below 0 °C (INIFAP station, La llave, San Juan del Rio, Queretaro). In the trial maize was sown at the end of May and harvested at the beginning of December, thereafter barley was sown which was harvested early May.

The experimental design was a randomized complete block design with two repetitions and 10 treatments, of which 5 that compare residue levels were used in this study (Table 1). The treatments comparing bed width were already reported in Saldivia-Tejeda *et al.* (2021). The plot size was 70 m long by 6 m (8 rows of maize) wide. The field was leveled at the beginning of the experiment in 2017, after which raised beds were formed. In conventional tillage, these beds were plowed every year, in treatments with permanent beds, only the furrows were reshaped every cycle. The maize hybrid was DK-2069, sown at 101,000 seeds/ha with 75 cm between rows, the barley variety was Josefa, sown at 120 kg/ha and 15 cm between rows. Barley fertilization was 183N-46P-60K-84S-2B-3.3Zn, 100 kg/ha KCl and diammonium phosphate and 120 kg/ha urea applied at sowing and 300 kg/ha ammonium sulfate, and 80 kg/ha urea applied 30 days after emergence. Barely was irrigated 4 times per cycle using flood irrigation. Weed, pest and disease management were done using conventional farmers' practice.

Table 1. Treatments evaluated in the San Juan del Rio III platform, corresponding to the percentages of residue retention, Querétaro, OI 2017-2018 and OI 2018-2019.

Treat-ment	Abbreviation	Tillage	Residue management maize	Residue management barley
1	CB, R	Narrow beds with conventional tillage	Remove all residues	Remove all residues
2	PB, 10%	Narrow permanent beds	Partial removal, leaving a stalk at 10% of plant height	Partially leave residues (10%), stubble height 7.5 cm, the rest of residue was removed
3	PB, 25%	Narrow permanent beds	Partial removal, leaving a stalk at 25% of plant height, removing the rest, afterwards chopping and spreading evenly the remaining 25%	Partially leave (25%), stubble height 20 cm, the rest of residue was removed
4	PB, 50%	Narrow permanent beds	Partial removal, leaving a stalk at 50% of plant height, removing the rest, afterwards chopping and spreading evenly the remaining 50%	Partially leave (50%), stubble height 20 cm, another 25% of the residues was chopped and spread in the field
5	PB, 100%	Narrow permanent beds	Leave all residues in the field, chopping and spreading them evenly	Leave 100%, stubble height 20 cm, the rest of the residues were chopped and spread in the field

Experiment 2: Metepec, State of Mexico

To study the effect of residues on frost damage we installed a field trial in the Sanjaya Rajaram Experimental station in Metepec, State of Mexico. The station is located at 2600 m above sea level, frost is highly likely to occur in each winter season. In the trial we evaluated the response of barley to frost under different tillage treatments and residue management. Additionally, we evaluated the use of salicylic acid as a stress reducing treatment.

The objective of the experiment was to answer the following research questions:

1) Is frost damage higher with reduced tillage?
2) When using reduced tillage, is frost damage higher when residues are left in the field?
3) Can frost damage be reduced by inducing stress tolerance by salicylic acid application?

In the field where the trial was located, maize was harvested in the first week of September, this was earlier than usual, with the objective that the stubble would have time to dry before planting barley. The trial was designed in three blocks, with each block having different tillage (conventional tillage, strip tillage and permanent raised beds), within these blocks, treatments with residue and salicylic acid application were evaluated (Table 2). Each treatment was evaluated with three repetitions in plots of 10 beds of 0.76 m wide and at least 12 m long.

Table 2. Treatments evaluated in the experiment in Metepec, Mexico.

No.	Abbreviation	Tillage	Stubble	Salicylic acid application
1	CB-K	Conventional	Keep	Without
2	CB-K-S	Conventional	Keep	With
3	PB-R	Permanent beds	Remove	Without
4	PB-K	Permanent beds	Keep	Without
5	PB-K-S	Permanent beds	Keep	With
6	ST-R	Strip till	Remove	Without
7	ST-R-S	Strip till	Keep	Without

Abbreviations: PB: Permanent beds, ST: Strip tillage, CB: Conventionally tilled beds, K: Keep all residues, R: Remove all residues, S: Salicylic Acid application.

Barley of the variety Josefa was planted on 19 October 2018 at a planting density of 120 kg/ha in 2 rows at 22 cm distance per bed (76 cm from furrow to furrow), a 50 kg N/ha fertilization was applied, in order to supply enough nitrogen for tillering. Temperature was monitored in the different treatments, using two iBotton sensors (Analog Devices Inc, Wilmington, USA) with two repeats per plot. The sensors were placed inside mesh bags and placed on stakes in such a way that the sensors were 5 cm above the surface of the ground. For the treatments with salicylic acid application, 2 effervescent Salicylic acid pills were dissolved inside a 20 L backpack. Applications were done 15 and 30 days after plant emergence. The data collected in the experiment were: soil surface temperature, emergence date, density of plants at emergence, frost mortality (percentage of live plants per plot after frost) and frost damage (necrosis in surviving plants). Due to the certainty of frost occurrence during heading, flowering or grain filling, yield was not considered in the experiment. Frost damage was scored using a 1 to 8 scale (Table 3).

Table 3. Scoring categories used to score frost damage.

Score	Percentage of damaged plants
1	0 - 12.5 %
2	12.5 - 25 %
3	25 - 37.5 %
4	37.5 - 50 %
5	50 - 62.5 %
6	62.5 - 75%
7	75 - 87.5 %
8	87.5 - 100 %

Experiment 3: Observations in modules and research platforms

In Mexico, CIMMYT operates 12 innovation hubs to promote sustainable agrifood systems (Gardeazabal *et al.*, 2023; Govaerts *et al.*, 2021). In these innovation hubs stakeholders work together to develop, validate, and implement new sustainable technologies. For this, they install research platforms, side–by–side comparisons and demonstration fields. This large number of fields and collaborators allows for the comparison of the effects of frost damage across a large number of observations. To obtain a better idea of the realities of frost damage in relation to residue management, collaborators were surveyed, and the e-Agrology database was used to compare the reported yield of small grains with and without residues.

Farm advisors from Queretaro, Guanajuato, Michoacan did indeed report to have observed greater frost damage in plots with more residues left on the surface. When this occurs during tillering, there is more damage in CA, however if it happens during later stages, the damage is similar between CA and conventional tillage, as the whole soil is similarly covered by the crop by then.

Data analysis

Data from the experiments is available at the CIMMYT Dataverse repository: https://hdl.handle.net/11529/10548972

Yield data from the San Juan del Rio III, Queretaro experiment was analyzed using ANOVA with the following models:

Yield = Treatment + Replicate + error

for each year.

Yield = Treatment*Year + error (Replicate/Treatment)

for repeated measures analyzing both years together.

The data from the Metepec experiment were analyzed by linear mixed models, using the *lmer()* function of the *lme4* package (Bates et al., 2015) in R (R Development Core Team, 2020). Pairwise comparisons and Tukey-adjusted p-values were obtained with the *emmeans()* function from the *emmeans* package (version 1.5.3; Lenth, 2021).

Y = Treatments + Replicate + (1+ Replicate|Time)

With Y = frost damage or plant survival.

Results

Experiment 1: The San Juan del Rio III research platform

In the 2017-2018 autumn-winter cycle, the planting date was December 21, 2017, which is considered within the optimal planting period. Frost occurred before the first auxiliary irrigation, all treatments were visibly affected by frost, except in the conventional tillage treatment (CB, R). During the growing season the temperatures were relatively low but suitable for the development of the crop (Fig. 1). The incidence of foliar diseases was minimal and was controlled with a single application of fungicide, in addition to the fact that environmental conditions (low relative humidity) led to low risk of foliar disease.

In the 2018-2019 autumn-winter cycle planting was later and took place on January 3, 2019. Low temperatures occurred mainly in mid-November and until the second half of January. Thereafter, the temperature was higher, which led to a high incidence of Septoria and less tillering of the plants, which led to low yields.

Fig. 1. Crop development as of March 21, 2018 (77 DAS), permanent beds with 100% stubble (left) and conventional tillage treatment (right).

In the 2017-2018 cycle, yield was similar in all treatments, with an average yield of 5.3 t/ha. The lowest yield was obtained in the treatment with 10% stubble and permanent beds (4.1 t/ha) while the highest yield was obtained with the treatment with permanent beds and 100% stubble (6.0 t/ha). In the 2018-

2019 cycle, yield differed significantly between treatments (Fig. 2). The highest yield was obtained by the treatment with permanent beds and 100% stubble retention, while the lowest yields were obtained with conventional tillage and permanent beds with 25% stubble retention. On average over both years, the treatment with permanent beds and 100% stubble yielded most (5.4 t/ha) while the treatments with conventional tillage (3.6 t/ha) and permanent beds and 10 or 25% stubble retention yielded less (3.9 and 3.4 t/ha respectively).

In both cycles, treatment with 100% stubble obtained the highest yield with 6.0 and 4.6 t/ha. In the 2018-2019 cycle in treatments with 50 and 100% stubble, a lower incidence of foliar diseases and more tillering was observed, which may have contributed to the higher yield.

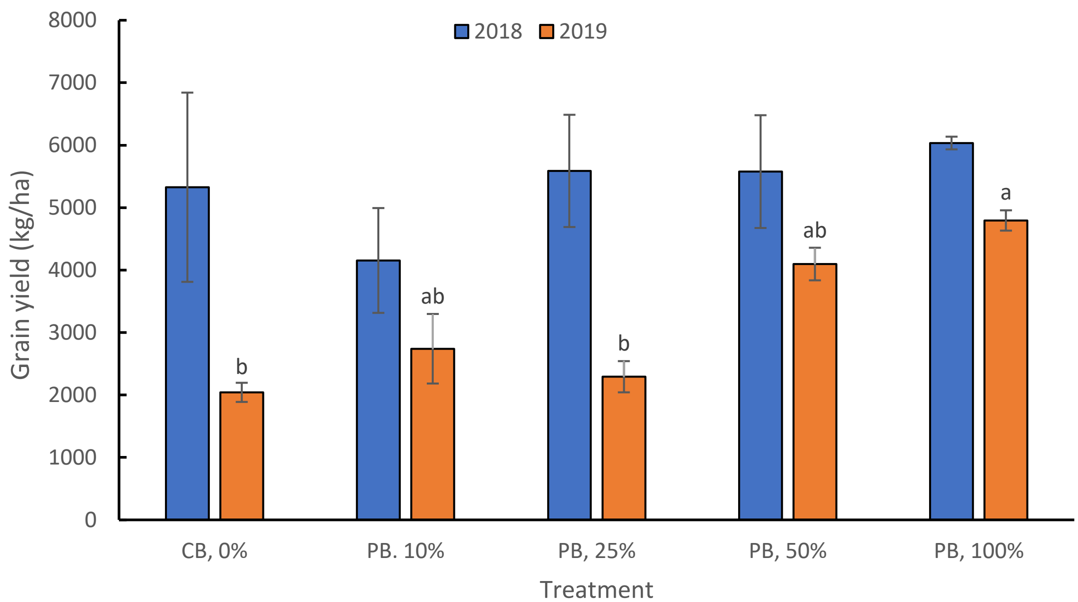

Fig. 2. Barley yield at 12% moisture under different tillage systems and percentages of maize stubble. Cycle OI 2017-2018 and OI 2018-2019 in the San Juan del Rio III platform, Querétaro.

Experiment 2: Metepec, State of Mexico

Temperature and humidity

Relative humidity did not differ between treatments, only one sensor in the treatment with strip tillage and residue retention indicated higher relative humidity values, however, as this was not the case in the repetition of the treatments, this was likely due to a sensor malfunction. Average humidity differed by 4% between the highest and lowest treatment value.

Minimum temperatures were lower in treatments with residues retention. While minimum temperatures in ST-R and PB-R were -4.5 ^{o}C, in PB-K temperatures were as low as -5.2 ^{o}C (Fig. 3).

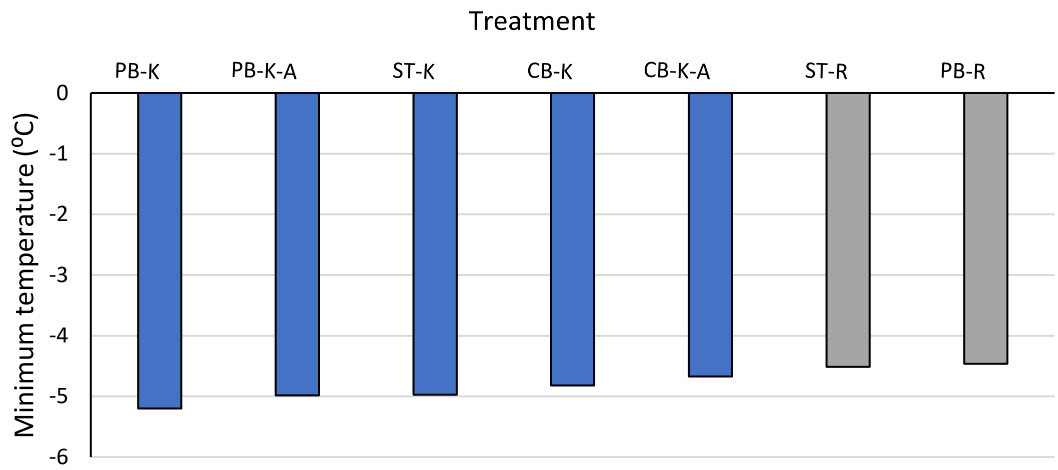

Fig. 3. Minimum observed temperature per treatment. Abbreviations: PB: Permanent beds, ST: Strip tillage, CB: Conventionally tilled beds, K: Keep all residues, R: Remove all residues.

Observed frost damage

Frost damage was not greater in treatments with permanent beds or strip tillage where residues were left in the field compared to where they were removed (Fig. 4). The treatment with conventional tillage and incorporated residues (CB-K) had higher frost damage scores than the other treatments troughout the experiment ($P<0.05$).

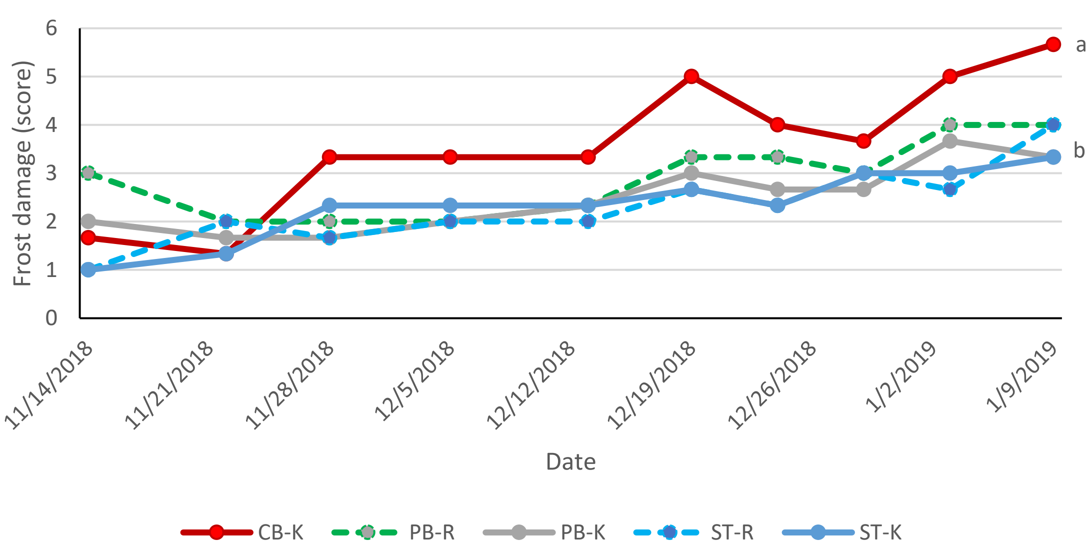

Fig. 4. Frost damage score over time in treatments without salicylic acid application in the experiment in Metepec. Abbreviations: CB: Conventionally tilled beds, PB: Permanent beds, ST: Strip till, K: Keep all residue in the field, R: Remove all residue.

A small effect of aspirin (salicylic acid) application was observed (P<0.001). Salicylic acid was only applied in treatments with conventionally tilled or permanent beds and full residue retention. In both cases, the treatment with salicylic acid application had a lower frost damage score than the equivalent treatment without salicylic acid application, indicating that it had more visually observed frost damage (Fig. 5).

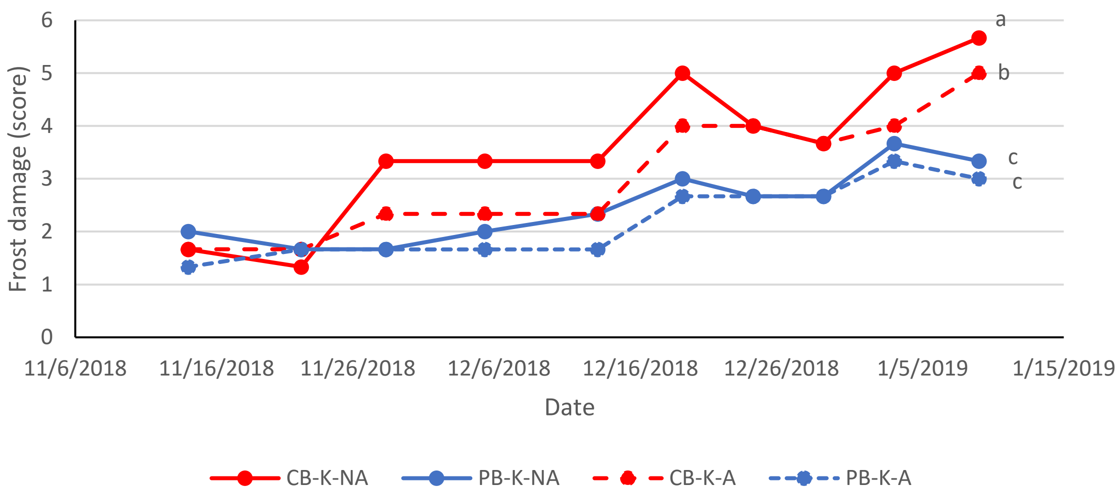

Fig. 5. Frost damage score in treatments with Salicylic acid application over time in the experiment in Metepec. Abbreviations: CB: Conventionally tilled beds, PB: Permanent beds, K: Keep all residue in the field, A: Salicylic acid application.

Plant survival was higher in treatments with tillage, mortality was lowest in conventionally tilled beds which had no mortality until the latest observation (Fig. 6). Survival was lower in strip till, but not significantly different from mortality in conventional beds. Plant survival was significantly lower in permanent beds (P=0.006), although overall plant mortality did not surpass 12% for PB-R, the treatment with the most mortality. Residue retention did not lead to higher mortality, on the contrary, both in strip till and permanent beds, the treatments without residues had higher mortality (P=0.004).

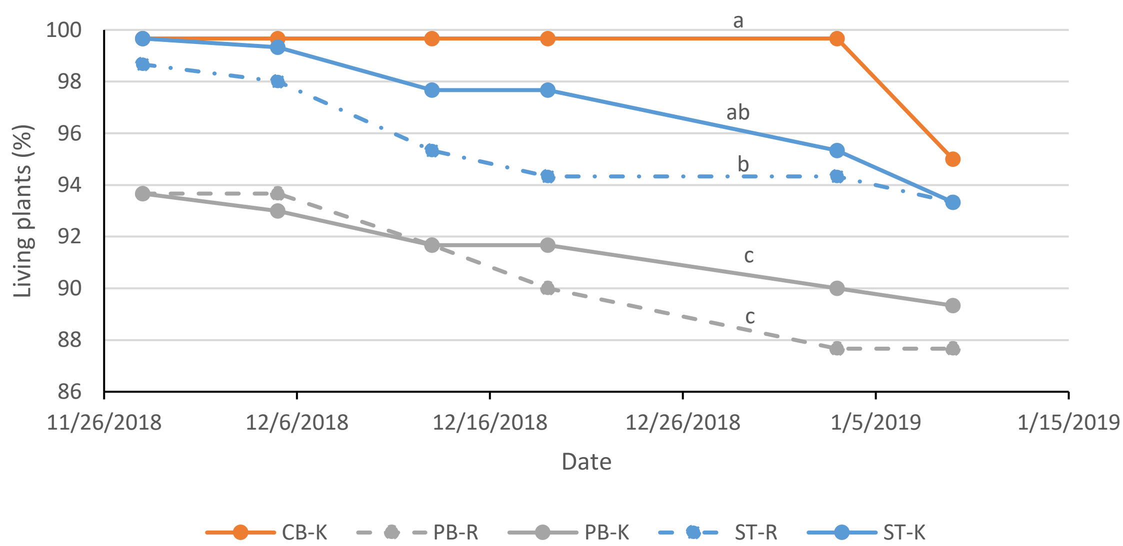

Fig. 6. Percentage of live plants per treatment over time in the experiment in Metepec. Abbreviations: CB: Conventionally tilled beds, PB: Permanent beds, ST: Strip till, K: Keep all residue in the field, R: Remove all residue. Scale of Y-Axis starts at 86% to better visualize differences.

Salicylic acid application showed a protective effect in permanent beds with residue retention (Fig. 7), as the treatment with salicylic acid had a higher number of living plants throughout the experiment ($P<0.001$). No effect was observed in conventional beds since these treatments suffered no mortality until the last date of observation.

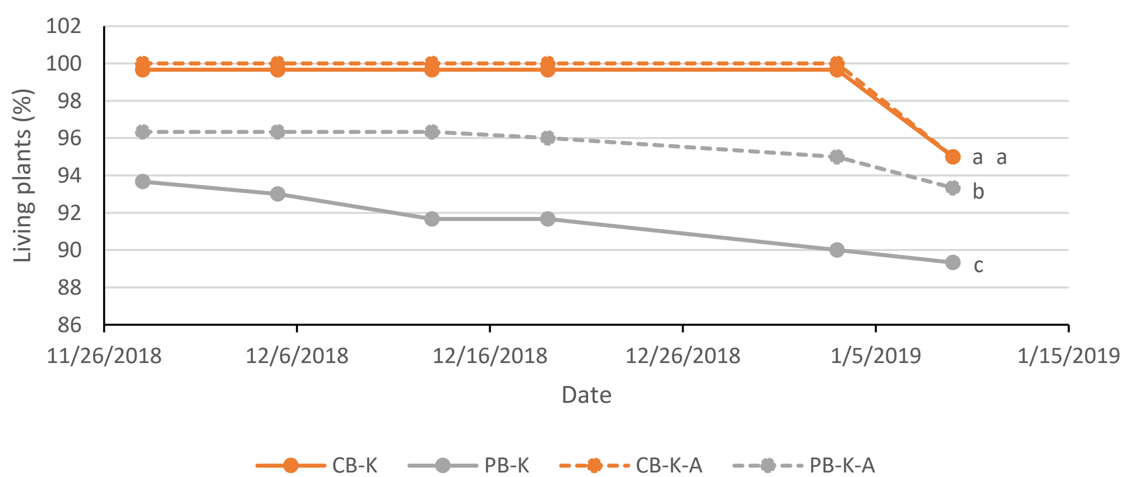

Fig. 7. Percentage of live plants in treatments with Salicylic acid application over time in the experiment in Metepec. Abbreviations: CB: Conventionally tilled beds, PB: Permanent beds, K: Keep all residue in the field, S: Salicylic acid application. Scale of Y-Axis starts at 86% to better visualize differences.

Experiment 3: Observations in modules and research platforms

Farmers' fields

The data from 235 innovation modules which had a side-by-side comparison of conventional tillage and CA with wheat or barley grown during the winter season were compared. Average yields were higher with CA, so there was no indication of lower yield in CA (Table 4). In barley yields were lower in CA than in CT in 8% of observations in barley and in wheat in 6% of observations, however it was not reported that whether this was due to frost damage. In general, it appears that the benefits of CA in terms of increased soil health, higher water retention, reduced production cost outweigh the risk of higher frost damage, and the risk of frost damage should not be an impediment for the implementation of CA.

Table 4. Average yield per crop and region in Mexico of wheat and barley grown in the autumn-winter cycle in innovation modules between 2012 and 2018.

	Conservation agriculture yield (t/ha)	**Conventional tillage yield (t/ha)**	**Number of observations**
Barley			
General	5.8	5.5	48
Guanajuato	5.6	5.3	37
Michoacan de Ocampo	7.3	7.3	1
Queretaro	6.4	6.3	10
Wheat			
General	6.3	6.1	184
Baja California	6.5	6.5	20
Baja California Sur	5.9	5.8	3
Guanajuato	6.3	5.8	1
Hidalgo	6.5	6.6	45
Michoacan de Ocampo	6.0	6.0	13
Oaxaca	5.8	4.4	2
Sinaloa	4.4	4.2	7
Sonora	6.4	6.3	92

Research platforms

In Irapuato, Guanajuato, there were two research platforms active during the 2019-2020 growing season, in Irapuato I wheat was grown and in Irapuato III barley (Fonteyne *et al.*, 2021b). A frost occurred on January 6, 2020, shortly after plant emergence and cold temperatures continued until January 16. The low temperatures generated greater visible damage in the treatments in CA, but the plants recovered quickly. Ultimately, yield was not affected as treatments in CA obtained slightly higher yields (Table 5).

Table 5. Yields obtained by type of tillage and irrigation in the research platforms Irapuato I and Irapuato III, Guanajuato during the 2019-2020 growing season. Data is yield at 12% moisture content in ton hectare^{-1} with standard error.

Tillage	Type of irrigation	Irapuato I	Irapuato III
Conventional tillage	Furrow	6.6 ± 0.1	6.6 ± 0.4
Conservation agriculture	Furrow	7.2 ± 0.1	7.6 ± 0.4
Conventional tillage	Drip	7.0 ± 0.2	7.9 ± 0.3
Conservation agriculture	Drip	7.1 ± 0.6	7.5 ± 0.4

Fig. 8. Frost-damaged plants on the Irapuato I platform, Guanajuato, January 6, 2020.

Fig. 9. Frost damage in plots in CA in the Irapuato III research platform, January 6, 2020.

Discussion

Conservation agriculture with higher levels of residue was associated with higher levels of frost damage during the tillering stage in the Bajío, both in the dedicated field trials as well as in observations in farmers' fields. This did not have negative effects on grain yield, however, as it seems that the other benefits of CA offset the negative effects that may occur due to frost damage.

Likewise, fodder oats yielded more under CA with different levels of residue retention than conventional tillage in a long term trial in San Luis Potosi, Mexico over a 25 year period, even though frost damage also occurred in the trial (Fonteyne *et al.*, 2019).

The trial in Metepec had variable results. The treatments with tillage had higher frost damage, but lower plant mortality than the treatments with less tillage. Keeping residues in the field did not increase frost damage or mortality, however, Aspirin or salicylic acid application showed a protective effect against frost mortality and may be an option to protect plants when frost stress is likely to occur. However, similar to the effect of tillage, it had a higher frost damage score.

Overall, wheat and barley in CA may present more symptoms of frost damage when frost occurs during the tillering stage, however this has no effect on yield. On the contrary, yield tends to be higher in CA. It is likely that plants in the tillering stage can quickly replace the damaged leaves and tillers, and the cold stress may even induce extra tillering, which may lead to more awns and more grain later on. Problems other than frost may have a larger effect on yield, such as the *Septoria* incidence in barley in the experiment in San Juan del Rio, Queretaro, and conservation agriculture could have had a beneficial effect on this, by increasing beneficial soil microbiology (Rieke *et al.*, 2022).

Conclusion

Conservation agriculture has many proven benefits for grain production in the Bajío, such as improved soil health, improved irrigation efficiency, reduced production costs, reduced greenhouse gas emissions and these benefits offset the negative effects of frost that may occur in region. While greater damage may occur when frost happens during the tillering stage, this does not affect yield and should not be considered a reason not to implement conservation agriculture.

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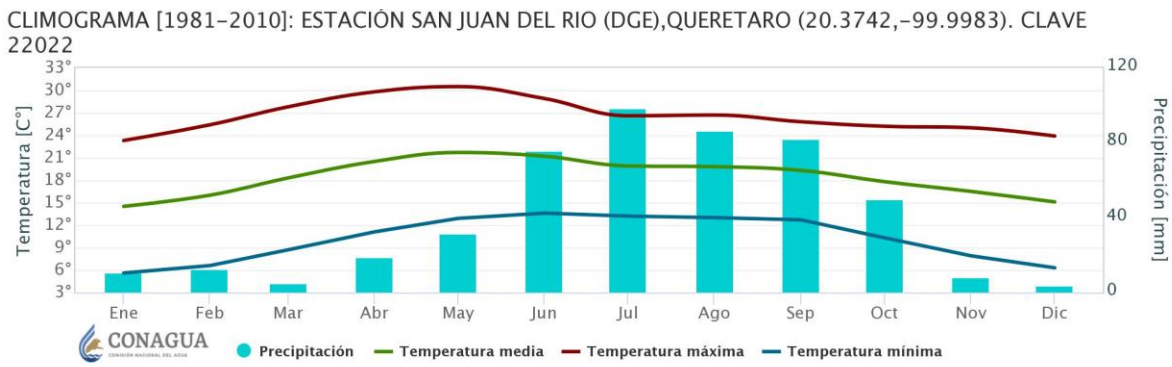
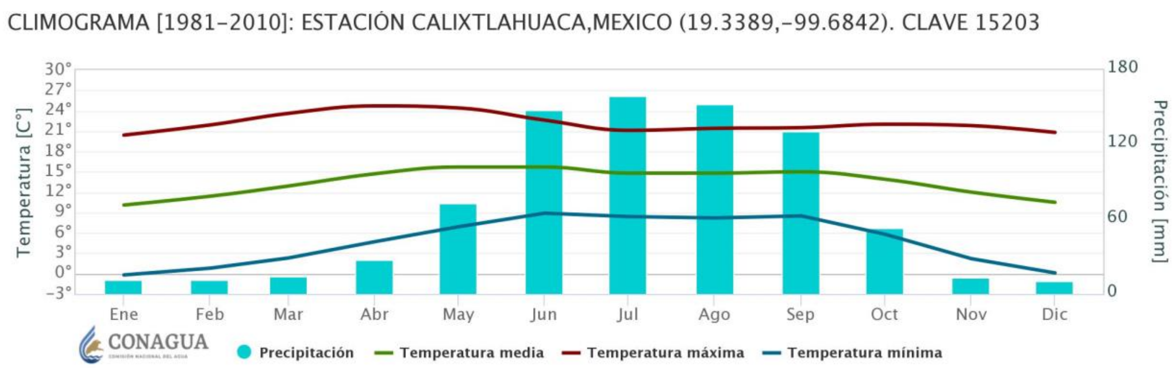
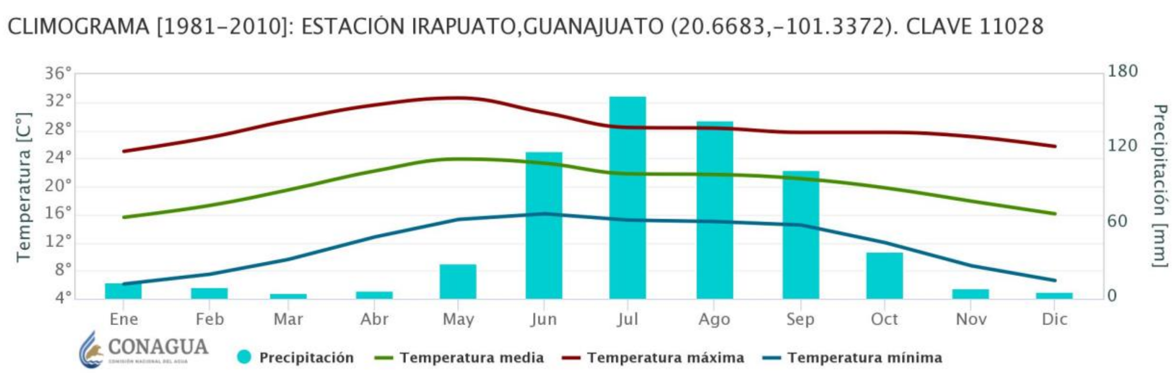
Supplementary materials



Supplementary figure 1. Climograma San Juan del Rio, Querétaro (Conagua, https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/climogramas-1981-2010)



Supplementary figure 2. Climatic conditions in Clixtlahuaca, Mexico state, clostest data to the Metepec station. (Conagua, https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/climogramas-1981-2010)



Supplementary figure 3. Climograma Irapuato, Guanajuato (Conagua, https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/climogramas-1981-2010)