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Weed management and tillage effect on rainfed maize production in three agro-ecologies in Mexico

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Abstract

Maize (*Zea mays* L.) is grown in a wide range of agro-ecological environments and production systems across Mexico. Weeds are a major constraint on maize grain yield, but knowledge regarding the best weed management methods is lacking. In many production systems, reducing tillage could lessen land degradation and production costs, but changes in tillage might require changes in weed management. This study evaluated weed dynamics and rainfed maize yield under five weed management treatments (pre-emergence herbicide, post-emergence herbicide, pre-emergence + post-emergence herbicide, manual weed control, and no control) and three tillage methods (conventional, minimum and zero tillage) in three agro-ecologically distinct regions of the state of Oaxaca, Mexico, in 2016 and 2017. In the temperate Mixteca region, weeds reduced maize grain yields by as much as 92% and the long-growing season required post-emergence weed control, which gave significantly higher yields. In the hot, humid Papaloapan region, weeds reduced maize yields up to 63% and pre-emergence weed control resulted in significantly higher yields than treatments with post-emergence control only. In the semi-arid Valles Centrales region, weeds reduced maize yields by as much as 65%, but weed management was not always effective in increasing maize yield or net profitability. The most effective weed management treatments tended to be similar for the three tillage systems at each site, although weed pressure and the potential yield reduction by weeds tended to be higher under zero tillage than minimum or conventional tillage. No single best option for weed management was found across sites or tillage systems. More research, in which non-chemical methods should not be overlooked, is thus needed to determine the most effective weed management methods for the diverse maize production systems across Mexico.

KEYWORDS
corn, integrated weed management, manual weed control, minimum tillage, no-till, Oaxaca, zero tillage

[Corrections added on 17 March 2022, after first online publication: the order of author names has been corrected in this version.]

1 | INTRODUCTION

Maize (*Zea mays* L.) is the staple food and the most important crop in Mexico and the Mexican state of Oaxaca as well. Weeds are the number-one biological constraint on maize yields worldwide and in North America can cause losses of over 50% (Jhala et al., 2014; Soltani et al., 2016). Oaxaca features extremely diverse agro-ecologies, ranging from humid tropical lowlands to temperate mountains, and over 90% of its inhabitants are classified as poor or extremely poor (CONEVAL, 2018). The state's many subsistence farmers need to improve their farming methods but are held back by a lack of research or technical assistance and the difficulties of developing effective recommendations for their numerous farm settings.

Soil degradation and erosion are widespread, due to extensive tillage, overgrazing and residue removal or burning in often-mountainous terrains (SEMARNAT, 2016). Farmers use disc or ox-drawn plows to prepare fields and remove residues, which serve as animal fodder or are burned. Conservation agriculture—a production system based on minimum tillage, permanent soil cover with residues or living crops, and cropping diversification—has been promoted to reduce soil degradation (Steward et al., 2018; Wall et al., 2020), but must be adapted to local conditions (Williams et al., 2018). Conservation agriculture has been shown to produce favourable results in Oaxaca, including reduced production costs, higher yields and improved soil health (Fonteyne et al., 2021, 2022; Núñez Peñaloza and Villa Alcántara, 2020; Osorio Alcalá, 2020a). Reduced tillage may go as far as 'zero' tillage—seeding directly into unplowed soil and crop residues—but in severely degraded or hard-setting soils, some tillage in the seeding zone may be necessary.

The adoption of conservation agriculture generally involves significant management changes for farmers, and aspects such as weed management are often perceived as the most difficult (Nichols et al., 2015; Singh et al., 2012). Weed populations and their dynamics change under conservation agriculture and control methods need to be adjusted (Singh et al., 2012), although, in the medium-to-long term, with adequate weed management, weed populations can decrease in conservation agriculture (Fonteyne et al., 2020). To obtain the long-term benefits of conservation agriculture, adequate weed management in the first years is key (Lee and Thierfelder, 2017) and an efficient control strategy will depend on agro-ecological conditions such as rainfall, temperature or local weed ecologies. Herbicides or manual controls, including hoe weeding or horse- or tractor-drawn weeders, are the most common weed management methods in Oaxaca. Herbicides are commonly cheap and old active ingredients (mainly paraquat, glyphosate and atrazine) and are applied using backpack sprayers. Farmers lack knowledge of the appropriate herbicides or their effective and safe use, so weed management is often poor.

Because of the lack of information about effective weed management in Oaxaca, we conducted trials to compare the effectiveness of five weed management methods (manual, pre-emergence herbicides, post-emergence herbicides, the combination of pre and post-emergence herbicides and an unweeded control) under three tillage systems (conventional, minimum and zero tillage) in 2016 and 2017. The trials were located in three agro-ecological regions of Oaxaca: the Mixteca (temperate subhumid), Papaloapan (hot and humid), and Valles Centrales (semi-arid), each with distinct production systems and weed flora, and we assessed the effects of the treatments on weed development, weed biomass production, and maize grain yield and profitability.

2 | MATERIALS AND METHODS

The trials were set up by farm advisors collaborating in the innovation hub fostered by CIMMYT in Oaxaca (Gardeazabal et al., 2021). In the hub, adaptive research is codesigned and implemented together with local farmers to improve farmers livelihoods while creating more sustainable production systems (Gardeazabal et al., 2021; Govaerts et al., 2021). In Oaxaca, the farmers expressed a lack of knowledge on weed management, especially under reduced tillage. The farm advisors thus set up similar trials adapted to the conditions of their region in order to generate recommendations. The trials were evaluated on farm (Papaloapan, Valles Centrales) or under similar conditions (Mixteca) which increased relevance and impact but complicated consistency in treatments and locations.

2.1 | Site description

The first site is in the 'Sitio Experimental Mixteca' research station in Santo Domingo Yanhuitlán, the Mixteca Region (Figure 1). Located at 2195 m above sea level (masl), it has Vertisol soils, a temperate subhumid climate, and average maize yields for the municipality of 1.1 t ha^{-1} in 2016 and 1.3 t ha^{-1} in 2017 (SIAP, 2020). The average rainfall was 855 mm year^{-1}, the average maximum monthly temperature was 24.5°C and the average maximum monthly temperature was 7.4°C in 2016 and 2017 (Figure 2). Maize in the region is generally sown at the end of May and harvested at the end of December. The second site is in the town of San Felipe Zihualtepec in the municipality of San Juan Cotzocón, Papaloapan Region. It is located at 60 m asl and has Luvisol soils, a hot humid climate, and average maize yields for the municipality of 3.4 t ha^{-1} in 2016 and 3.6 t ha^{-1} in 2017 (SIAP, 2020). The average rainfall was 1872 mm year^{-1}, the average maximum monthly temperature was 30.7°C and the average maximum monthly temperature was 19.8°C in 2016 and 2017 (Figure 2). Maize in the region is generally sown in the beginning of June and harvested at the end of November. The third location was in the town of Ciénega de Zimatlán in the municipality with the same name, Valles Centrales Region. The original site was changed in 2017 to a nearby field, because the collaborating farmer from 2016 did not want to continue the trial. Both fields are located at 1552 m asl, have Vertisol soils, a hot semi-arid climate, and average maize yields for the municipality of 1.0 t ha^{-1} in 2016 and 0.9 t ha^{-1} in 2017 (SIAP, 2020). The average rainfall was 825 mm year^{-1} but variation was large, with 595 mm in 2016 and 1055 mm in 2017. The average maximum monthly temperature was 30.1°C and the

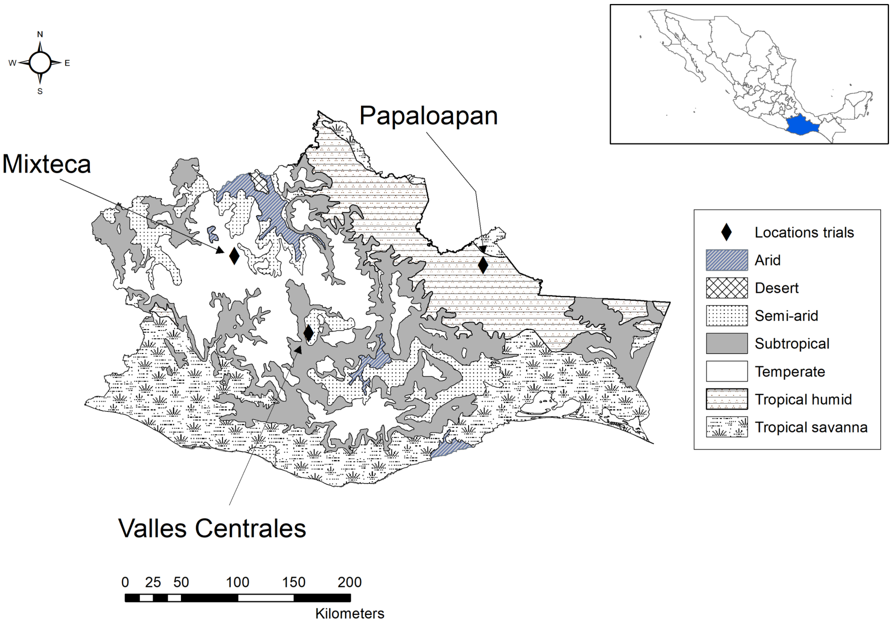

FIGURE 1 Location of the trial sites in specific regions (the Mixteca, Papaloapan, and Valles Centrales) of the state of Oaxaca, Mexico, and the state's location in Mexico

average maximum monthly temperature was 12.1°C in 2016 and 2017 (Figure 2). Maize in the region is generally sown at the end of June and harvested at the end of November. Soils in Valles Centrales are generally degraded from heavy tillage and crop residue removal for fodder, and neither site used in Valles Centrales was apt for zero tillage. All three sites were rainfed, no irrigation was applied in the experiments. Before the installation of the experiments, all three sites were managed with conventional tillage. No herbicide-resistant weeds were present at the experimental sites.

2.2 | Description of experiments

The design of the study was to evaluate fifteen combinations of tillage and weed management treatments that were tested at each of the three sites. At each site, there were three trials with a different tillage system: zero tillage (ZT), minimum tillage (MT) and conventional tillage (CT). At Valles Centrales, the ZT trial was not included because the terrain was not suitable for ZT. Within each trial, five weed management treatments were evaluated in three replicates in a randomised complete trial design. Tillage trials at all locations were 50 × 14.4 m, with plots 10 m long and 4.8 m wide, containing six rows of maize lengthwise with a row separation of 0.8 m. The maize was planted using a seed drill between June and August, depending on the onset of summer rains, as all experiments were rainfed. Weed management treatments were conducted similarly in all tillage trials and reflected common local practices and available herbicides or equipment, as well as weather, soil moisture and weed species (Table 1), and comprised combinations of the following:

MAN, manual control. Weeds were manually controlled after reaching 20 cm in height approximately 20–25 days after sowing (DAS), as per the common practice. Weeding was carried out with a hand hoe by 4 to 10 workers per hectare, depending on the quantity of weeds, or using a tractor-drawn cultivator.

PRE, pre-emergent herbicide. Only a pre-emergent herbicide with residual effect was applied before sowing.

POST, post-emergent herbicide. When weeds reached 5–10 cm in height, approximately 20–25 DAS, and based on soil moisture conditions and the types of weeds present, a selective herbicide or an unselective direct contact herbicide (glufosinate) was applied.

PRE + POST, integrated weed management. A pre-emergent herbicide was applied, followed by post-emergence control using either selective herbicides or manual controls. The post-emergence application was only applied if considered necessary based on weed incidence.

CONT, control. No weed management was practiced.

The herbicides used were glyphosate, (Faena Fuerte 360, 363 g a.i. L^{-1}, SC, Monsanto Commercial or Coloso Total 360, 360 g a.i. L^{-1}, SL, Syngenta Agro), acetochlor + atrazine (Harness Xtra, 516 and 204 g a.i. L^{-1}, WC, Monsanto Comercial), dicamba + atrazine (Marvel, 132 + 205 g a.i. L^{-1}, SC, Syngenta Agro), nicosulfuron (Sanson 60 OD, 60 g a.i. L^{-1}, SC, Syngenta Agro), atrazine + S-metolachlor (Primagram Gold, 370 and 290 g a.i. L^{-1}, SC, Syngenta Agro), 2,4-D (Hierbamina, 479 g a.i. L^{-1}, EC, Syngenta Agro or Herbipol 4-EB, 481 g a.i. L^{-1}, EC, Polaquimia), foramsulfuron + iodosulfuron (Maister, 300 and 20 g a.i. L^{-1}, GR, Bayer de Mexico), atrazine (Atrazina 45 or Gesaprim, 480 g a.i. L^{-1}, GR, Syngenta Agro) and glufosinate (Tarang 150 Sl, 150 g a.i. L^{-1}, SC, UPL Agro Mexico).

All management practices not included in the treatment descriptions were performed according to regional recommendations and standard practices for the contrasting site ecologies; so, for example, maize varieties and fertilisation level differed among sites (Table 2). Common local varieties were used, no herbicide-tolerant varieties are used in Mexico. In ZT, maize was always

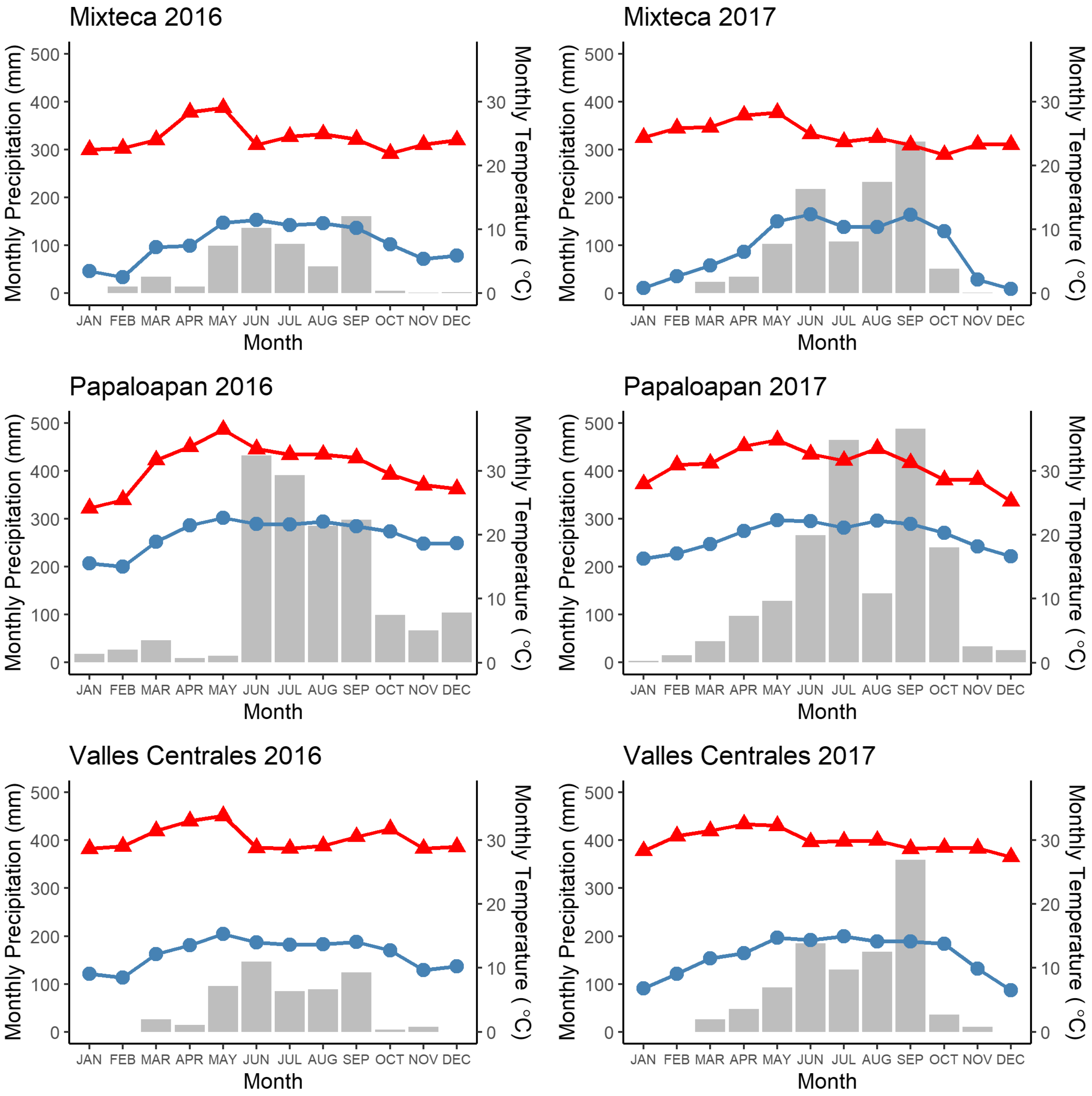

FIGURE 2 Monthly average minimum (blue circles) and maximum (red triangles) temperature and monthly precipitation (grey bars) per site and year. Data were obtained from the closest meteorological station to the site: Mixteca: Santo Domingo Yanhuitlán, Papaloapan: Maria Lombardo, San Juan Cotzocón, 2017, Valles Centrales: Zimatlán de Álvarez

direct-seeded, whereas MT and CT differed according to local practices and field conditions (Table 2). In ZT and MT, residues were chopped before sowing and spread uniformly over the field, while in CT, they were removed after harvest (farmers typically use them as fodder). Before chopping residues, we applied glyphosate pre-sowing at 363–1089 g a.i. ha^{-1}, depending on the types of weeds present. In Papaloapan, preplant tank-mix glyphosate and 2,4-D were applied at 1800 + 962 g a.i. ha^{-1} to control broadleaf weeds and sedges. Doses varied because of spot treatments and only live weeds were sprayed, rather than the whole field, as per local practice. A standard sowing density of 62 500 seeds per hectare was used in all locations, keeping the row separation of 0.8 m and plant-to-plant distance in rows of 0.2 m.

2.3 | Data collection and calculations

Weed density and biomass were sampled several times each growing season (Table 2). For each sampling, we marked an area of 1 × 1 m and counted the number of narrowleaf and broadleaf weeds

TABLE 1 Overview of the applications per weed management treatment per site and year

Location	Year	Treatment	First application	Second application
Mixteca	2016	MAN	1 hand hoeing	1 hand hoeing
		PRE	Atrazine + Acetochlor	
		POST	Dicamba + Atrazine	Foramsulfuron + Iodosulfuron
		PRE + POST	Atrazine + Acetochlor	Dicamba + Atrazine, 1 hand hoeing
Mixteca	2017	MAN	1 hand hoeing	1 hand hoeing
		PRE	Atrazine (720 g a.i. ha^{-1})	
		POST	Dicamba + atrazine	
		PRE + POST	Atrazine (1440 g a.i. ha^{-1})	1 hand hoeing
Papaloapan	2016	MAN	1 hand hoeing	
		PRE	Atrazine	
		POST	Glufosinate[a]	
		PRE + POST	Atrazine	Not required
Papaloapan	2017	MAN	1 hand hoeing	
		PRE	Atrazine	
		POST	Glufosinate[a]	
		PRE + POST	Atrazine + Acetochlor	Not required
Valles Centrales	2016	MAN	1 hand hoeing	
		PRE	Atrazine + Acetochlor	
		POST	Dicamba + Atrazine + Nicosulfuron	
		PRE + POST	Atrazine + Acetochlor	Not required
Valles Centrales	2017	MAN	1 interculture with tractor	1 hand hoeing
		PRE	Atrazine + S-Metolachlor	
		POST	2,4-D	Dicamba + Atrazine
		PRE + POST	Atrazine + S-Metolachlor	Dicamba + Atrazine

Note: In the control treatment CONT, no herbicide was applied except for glyphosate pre-plant application.

Abbreviations: MAN: Manual weed management, PRE: Weed management with pre-emergence herbicide, POST: Weed management with post-emergence herbicide, PRE + POST: Weed management with pre- and post-emergence herbicides.

[a] Glufosinate as a post-emergence application was applied directly on the weeds using a backpack sprayer.

within. Above-ground biomass was harvested and air-dried to determine weed dry biomass; in Valles Centrales, we weighed only fresh weed biomass and used a moisture content of 80% to convert to dry weight. Weed sampling continued until the maize plants reached the V7 growing stage (collar of seventh leaf visible) and, in the Mixteca, weeds were also sampled after harvest. In Papaloapan, weed biomass was sampled only once in 2016 and in 2017 three times to obtain more detail on weed development. Maize grain yield was determined by harvesting all plants in the 16 m^2 harvest area of each plot (10 m × 2 rows 0.80 m apart). Moisture content was adjusted to 14%.

The profitability of weed management was calculated using partial budget analysis, considering the control treatment without weed management as the base scenario. The cost of weed management was subtracted from extra income due to the higher yield, which was calculated as the difference in yield between the treatment and the control multiplied by the grain price at harvest. Costs for manual control were calculated as hired labour. Grain prices were obtained from local farmers and were 6 MXN kg^{-1} in Valles Centrales in both years, 5 and 4.5 MXN kg^{-1} in 2016 and 2017, respectively, in the Mixteca and 4 MXN kg^{-1} in Papaloapan in both years.

2.4 | Data analysis

Our study data are freely available in Dataverse at https://data.cimmyt.org, reference number 11529/10548568. All statistical analyses were performed in R version 3.6.0 (R Core Team, 2020). The three sites had very different agro-ecological conditions, with large differences in yield, and therefore were analysed separately. A complication in the statistical analysis was that due to practical concerns, the tillage systems at each site were not replicated. The data were therefore first analysed with model 1 for weed biomass and weed density for each sampling day and for maize grain yield, to evaluate whether the observations in the 2 years could be analysed as repetitions.

$$Y_{ijkm} = m + T_i + M_j + A_k + (TM)_{ij} + (TA)_{ik} + (MA)_{jk} + (TMA)_{ijk} + R_{(ikm)} + \text{error}_{ijkm} \quad \text{(model 1)}$$

TABLE 2 Overview of tillage systems, experiment management and data collection in days after sowing (DAS) per site and year

	Valles Centrales	Mixteca	Papaloapan
ZT	NA	Direct seeded	Direct seeded
MT	Disc harrowing in 2016; disc plowing, one pass with disc harrow and vertical tillage in 2017	One pass with a subsoiler	One pass with disc harrow
CT	Disc plowing followed by two passes with disc harrow	Disc plowing followed by one pass with disc harrow	Four passes with disc harrow
Maize variety 2016	CSTHW14001 (pre-commercial hybrid, CIMMYT)	ST10W (hybrid, Semilla el Trebol)	P4082W (hybrid, Pioneer)
Maize variety 2017	Criollo Bolita (landrace)	Ares (hybrid, Unisem)	H-565 (hybrid, INIFAP)
Fertilization (N-P-K kg ha^{-1})	60-55-50	106-60-60	100-60-120
Sowing date 2016	16 July	20 June	01 August
Weed density data collection 2016 (DAS)	14, 20, 31	−2, 14, 42	10, 20, 30, 41
Weed biomass data collection 2016 (DAS)	31	−2, 14, 42	100
Sowing date 2017	05 July	23 June	12 July
Weed density data collection 2017 (DAS)	21, 32, 39, 46	20, 39, 52, 207	33, 43, 53
Weed biomass data collection 2017 (DAS)	21, 32, 39, 46	20, 39, 52, 207	33, 43, 53

Abbreviations: CT, Conventional tillage; DAS, Days after sowing; MT, Minimum tillage; ZT, Zero tillage.

With Y being the response variable, m the overall mean, factor T tillage system *i* (CT, MT or ZT), and factor M weed management *j* (CONT, MAN, PRE, POST or PRE + POST), A the factor of cropping year *k* and R the effect of replicate *m*. T, M and A were considered fixed effects, while R was considered as independent random factor with zero means and some variance and nested in tillage system and year.

In almost all cases, there were significant year × tillage system and year × weed management interactions, and tillage system × weed management interaction in Mixteca and Papaloapan. Because of these interactions and because of the complication of having no replicate of tillage system at each site, the data were analysed per tillage trial separately, considering each tillage trial at each site as a different experiment. Differences in weed biomass, weed density and maize grain yield between treatments were therefore analysed for each sampling date per tillage system and year with the model:

$$Y_{jm} = m + M_j + R_m + \text{error}_{jm} \quad \text{(model 2)}$$

With *Y* being the response variable, m the overall mean and M the effect of weed management I and *R* the effect of replicate *k*. The models were analysed using the *glm* and *aov* functions from the 'stats' package, which performs a generalised linear model and an ANOVA, respectively. *Post hoc* analysis was performed with the HSD function from the 'agricolae' package, which performs Tuckey's honestly significant difference test.

3 | RESULTS

3.1 | Mixteca trial

In the Mixteca, broadleaf weeds accounted for 97.5% of all observed weeds, with *Tithonia tubiformis* (Jacq.) Cass., *Oxalis lasiandra* Zucc. and *Lysimachia arvensis* (L.) U. Manns & Anderb being the most common species. Weed biomass increased quickly after 20 DAS, while weed density did not, mostly because *Tithonia tubiformis*, the most dominant weed at the site, grows very large, and a small density can produce a large biomass.

Weed biomass and weed density were significantly influenced by weed management treatments in Mixteca (Figure 3). In 2016 at 14 DAS, weed management had a significant effect on weed biomass in ZT, but only a marginally significant effect in MT ($p = 0.057$) and no effect in CT. Similarly, weed density was marginally different between treatments in ZT ($p = 0.051$), but not in MT or CT at 14 DAS. At 42 DAS, weed management had a significant effect on weed biomass in all tillage systems, while weed density was only marginally different between the different management treatments in ZT ($p = 0.060$) and MT ($p = 0.082$) but not in CT. In 2017, at 20 DAS, there were no differences in weed biomass or density between weed management treatments in all three tillage systems. At 39 DAS, weed biomass was significantly different between treatments in MT and ZT, but not in CT, while weed density only differed between treatments in MT. At 52 DAS, weed biomass was significantly different between management

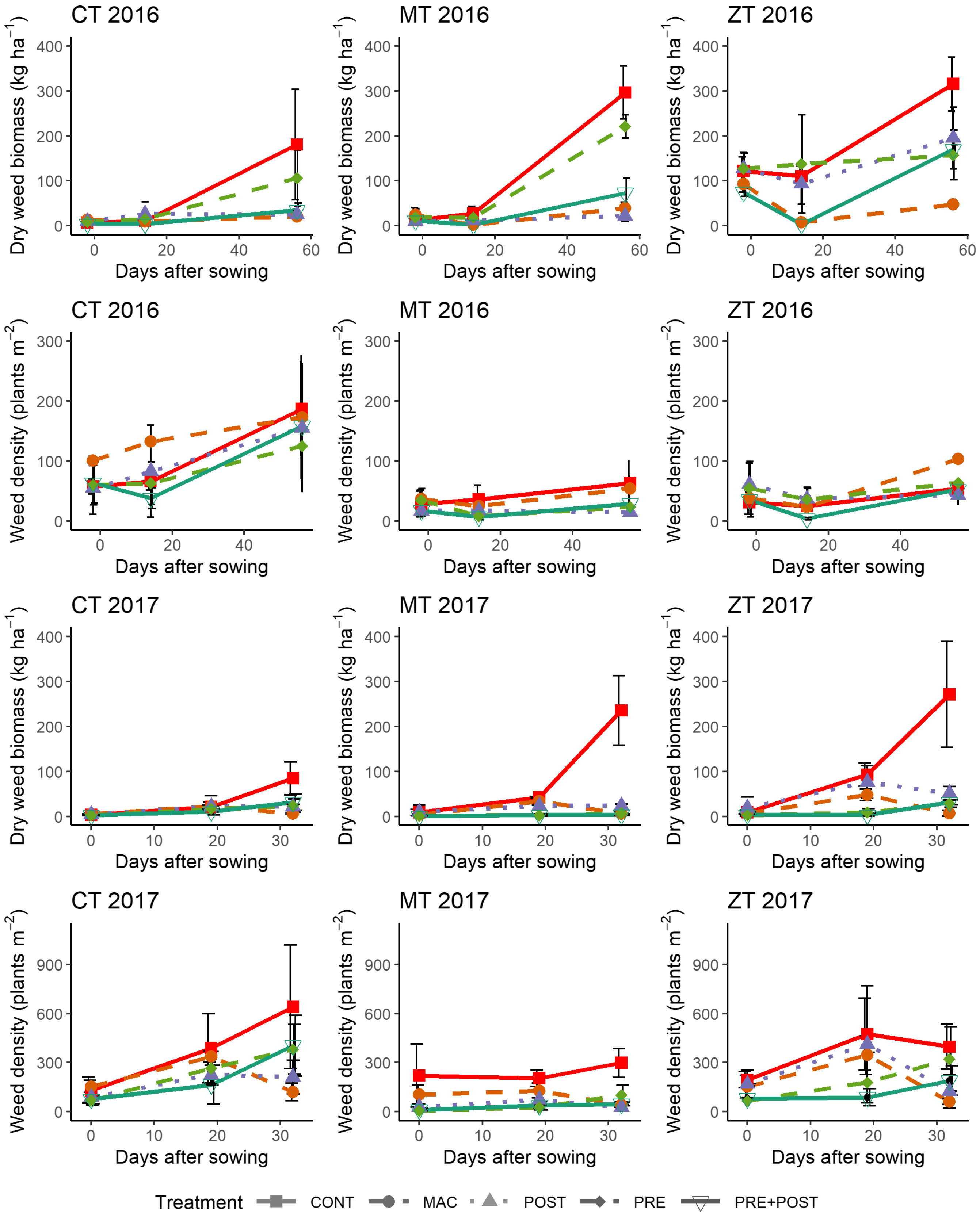

FIGURE 3 Weed biomass and weed density per year, tillage and weed management on different sampling dates in the trial in the Mixteca Region of the state of Oaxaca, Mexico. CT: Conventional tillage, MT: Minimum tillage, ZT: Zero tillage, CONT: Control treatment without weed management, MAN: Manual weed management, PRE: Weed management with pre-emergence herbicide, POST: Weed management with post-emergence herbicide, PRE + POST: Weed management with pre- and post-emergence herbicides

treatments in all three tillage systems, while weed density was significantly different between weed management treatments in ZT and MT, but only marginally in CT ($p = 0.084$).

Differences in weed biomass and weed density among treatments were in line with the moment of application, with CONT almost always having the highest weed biomass and density, PRE and PRE + POST having a low weed density initially and MAN and POST having a lower weed biomass and density after application. In 2017, a higher dose of atrazine was applied in PRE + POST than in PRE and while density and biomass were numerically higher in PRE than in PRE + POST, the differences were not significant. Overall, weed management was more important in ZT than in CT, with CT having lower weed biomass in all treatments in both years compared to ZT and less significant effects of treatments.

Maize grain yield was affected by the weed management treatments in all tillage systems, to varying degrees (Figure 4). Average yield was 6.6 ± 2.6 t ha^{-1} in CT, 6.7 ± 3.0 t ha^{-1} in MT and 5.7 ± 3.4 t ha^{-1} in ZT over all weed management treatments, while excluding CONT it was 7.2 ± 2.4 t ha^{-1} in CT, 7.9 ± 1.8 t ha^{-1} in MT and 6.8 ± 2.8 t ha^{-1} ZT. Under MT and ZT, the average difference between the weed management treatments and CONT was the largest (6.9 and 7.0 t ha^{-1} on average), while under CT, the difference between CONT and weed management treatments was smaller (3.6 t ha^{-1} on average). In all three tillage systems, the treatments with post-emergence control (MAN, POST and PRE + POST) obtained the numerically highest yields. In CT, however, there were no significant differences between treatments in 2017, a year with abundant rainfall, and only POST yielded significantly higher than CONT in 2016. In MT and ZT on the other hand, the effect of weed management was stronger. CONT always yielded significantly lower than the treatments with post-emergence control, and in 2016, PRE was also significantly lower yielding than the treatments with post-emergence control while not different from CONT. Overall, yield data thus indicate the importance of post-emergence weed control to obtain the highest yield in Mixteca.

3.2 | Papaloapan trial

In Papaloapan, 49% of weeds were broadleaf weeds and 51% narrowleaf. In 2016, 69%, 69% and 62% of weeds were broadleaf weeds in MT, ZT and CT, respectively. On 41 DAS, broadleaf biomass was 400 g/m^2 and narrowleaf biomass was 121 g/m^2 MT and ZT while it was 618 and 164 g/m^2, respectively, in CT. In 2017, 47 and 38% were broadleaf weeds in ZT and MT in 2017, respectively, and 19% in CT. *Spermacoce latifolia* Aubl. and *Sida rhombifolia* L. were the main species observed in ZT and MT, while narrowleaf weeds were more common in CT but the species could not be identified.

The weed control treatments were effective in both years in reducing weed biomass and weed density in comparison with the control treatment in all tillage systems (Figures 5 and 6). In treatments with PRE + POST, weed incidence was low at time when post-emergence herbicides should be applied. The decision was therefore taken not to apply them, because from an integrated weed management point of view they were unnecessary and from a farmer's point of view they were uneconomical. In 2016, PRE and PRE + POST were thus the same,

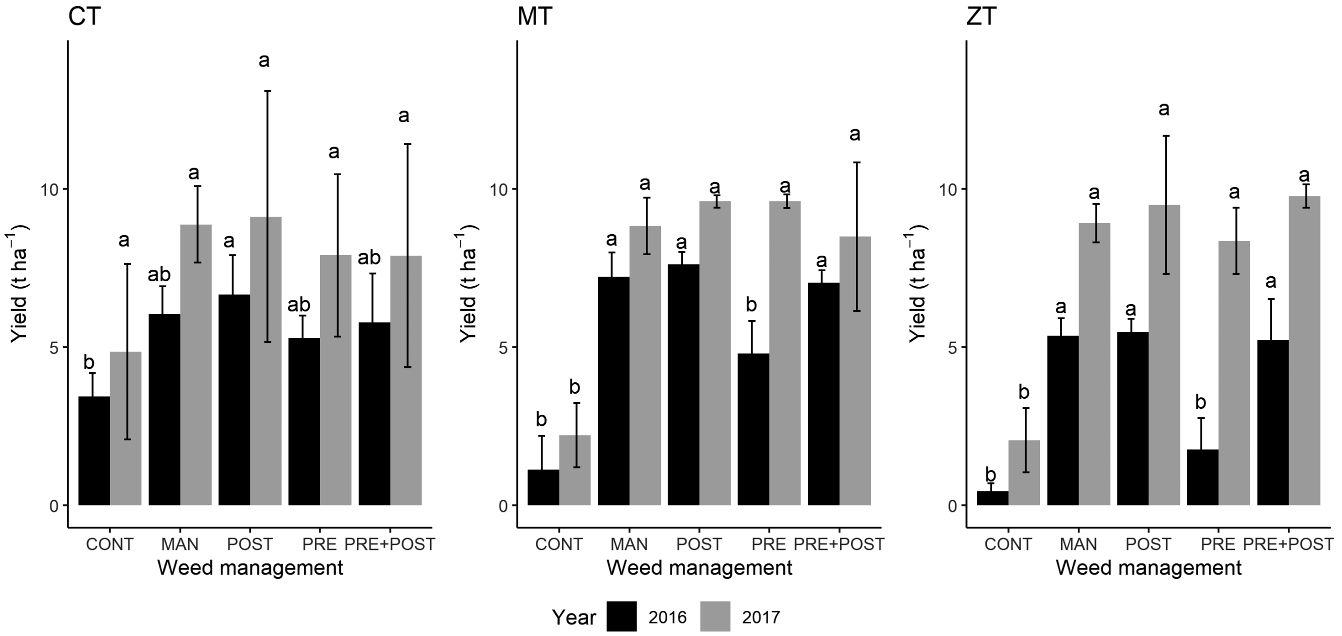

FIGURE 4 Maize yield with different weed management treatments in the Mixteca Region of the state of Oaxaca, Mexico, in 2016 and 2017. Vertical bars indicate standard error. Treatment means with a common letter are not significantly different in a given year and tillage system at $p < 0.05$. CT: Conventional tillage, MT: Minimum tillage, ZT: Zero tillage, CONT: Control treatment without weed management, MAN: Manual weed management, PRE: Weed management with pre-emergence herbicide, POST: Weed management with post-emergence herbicide, PRE + POST: Weed management with pre- and post-emergence herbicides

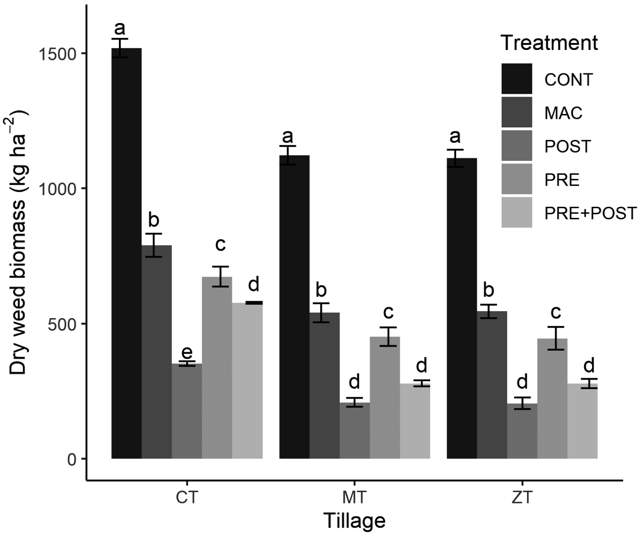

FIGURE 5 Biomass of weeds per tillage and weed management in the trial in the Papaloapan Region of the state of Oaxaca, Mexico, in 2016 at 41 DAS. Treatment means with a common letter are not significantly different in a given tillage system at $p < 0.05$. Vertical bars indicate standard error. CT: Conventional tillage, MT: Minimum tillage, ZT: Zero tillage, CONT: Control treatment without weed management, MAN: Manual weed management, PRE: Weed management with pre-emergence herbicide, POST: Weed management with post-emergence herbicide, PRE + POST: Weed management with pre- and post-emergence herbicides

while in 2017, in PRE only, atrazine was applied, while in PRE + POST, acetochlor and atrazine were applied in pre-emergence. Consequently, PRE had significantly higher weed biomass at 43 and 53 DAS in 2017 in CT and MT, though not in ZT. In 2016 there were no weeds 10 and 20 DAS in ZT and MT, and very few in CT, as a result of a lack of rainfall in the first 20 days after sowing. At 30 and 41 DAS, weed density increased, with the highest weed density in MAN in all three tillage systems and the lowest weed density and biomass in POST.

In 2017, there was a significant effect of weed management treatment on weed biomass and weed density at all sampling times in all tillage systems. At 33 DAS, PRE and PRE + POST had significantly lower weed biomass and weed density than POST, CONT and MAN in all three tillage systems. Afterwards, at 43 DAS, MAN and POST had 0 weed biomass and weed density in all tillage systems due to the recent application of these treatments, and weed density and biomass remained low in these treatments at 53 DAS, PRE and PRE + POST had significantly lower weed than biomass than CONT in all three tillage systems. In CT and MT, PRE + POST had lower weed biomass and density than PRE, likely because in PRE + POST atrazine and acetochlor were applied and in PRE only atrazine. Overall, there was a higher weed density and biomass in CONT in CT than in ZT and MT at every sampling date.

Overall, weed management system had a significant effect on maize grain yield. Average yield was 3.0 ± 0.9 t ha^{-1} in CT, 2.8 ± 1.0 t ha^{-1} in MT and 2.4 ± 0.8 t ha^{-1} in ZT over all weed management treatments and 3.3 ± 0.8 t ha^{-1} in CT, 3.1 ± 0.9 t ha^{-1} in MT and 2.7 ± 0.7 t ha^{-1} ZT excluding CONT (Figure 7). In Papaloapan, the average difference between the weed management treatments and CONT was smaller than in Mixteca at 1.3 t ha^{-1} on average and not different between the tillage systems. In all three tillage systems, the treatments with pre-emergence control (PRE and PRE + POST) tended to obtain significantly higher yields than POST and MAN. The combination of atrazine and acetochlor in PRE + POST in 2017 did not lead to higher yields compared to PRE, despite the lower weed density and biomass observed in MT and CT. Overall, the effects of management treatments on yield were largely similar between the tillage systems. Yield data indicate the importance of pre-emergence weed control to obtain the highest yield in Papaloapan.

3.3 | Valles Centrales trial

In Valles Centrales, 61% of observed weeds were broadleaf and 39% narrowleaf. The main weed species observed were *Simsia amplexicaulis* (Cav.) Pers. and *Portulaca oleracea* L. Weed incidence was low in 2016, therefore in the PRE + POST treatment, the application of post-emergence herbicide was not needed and PRE and PRE + POST had the same applications. In 2017, weed density was higher and in the PRE + POST treatment an application of dicamba and atrazine was considered necessary. MAN consisted of one hand hoeing in 2016, this proved to be insufficient as weed density was on average higher than in CONT in CT, though not in MT. In 2017 MAN consisted of one interculture done with a tractor followed by a hand hoeing. This proved to be more effective; however, weed density and biomass were not different from CONT after weeding.

In 2016, weed management treatments did not significantly affect weed biomass in either tillage system, though variation was large (data not shown). In CT, there was only a significant difference in weed density 20 DAS, with PRE, POST and PRE + POST having lower density than CONT and MAN (Figure 8). Under MT in 2016, there was only a significant difference in weed density 31 DAS, with PRE, POST and PRE + POST having lower density than CONT and MAN, although at 14 DAS weed density was lower in the MAN, PRE, POST and PRE + POST than in CONT ($p = 0.072$).

Similarly, in 2017, in CT, there was only a significant effect of weed management on weed density at 46 DAS, with PRE, PRE + POST and POST having significantly lower weed density than CONT. In CT, weed biomass was not significantly different between weed management treatments. In 2017, there was a significant effect of weed management on weed density at all sampling times in MT, with PRE and PRE + POST being lower than POST, MAN and CONT at all sampling times. In MT, at 32 and 39 DAS all treatments had lower weed biomass than CONT, while at 46 DAS only PRE and PRE + POST had significantly lower weed biomass.

Overall, the effect of treatments on weed incidence was stronger in MT than CT and treatments with pre-emergence application had the lowest weed incidence.

In 2016, MT gave numerically higher yields than CT, suggesting the effect subsoiling (MT) can have on maize yield in production systems like that of Valles Centrales (Figure 9). In 2017, yield was low in all tillage systems due to excessive rainfall. In 2016, weed management did not affect yield in any tillage system, although CONT under MT

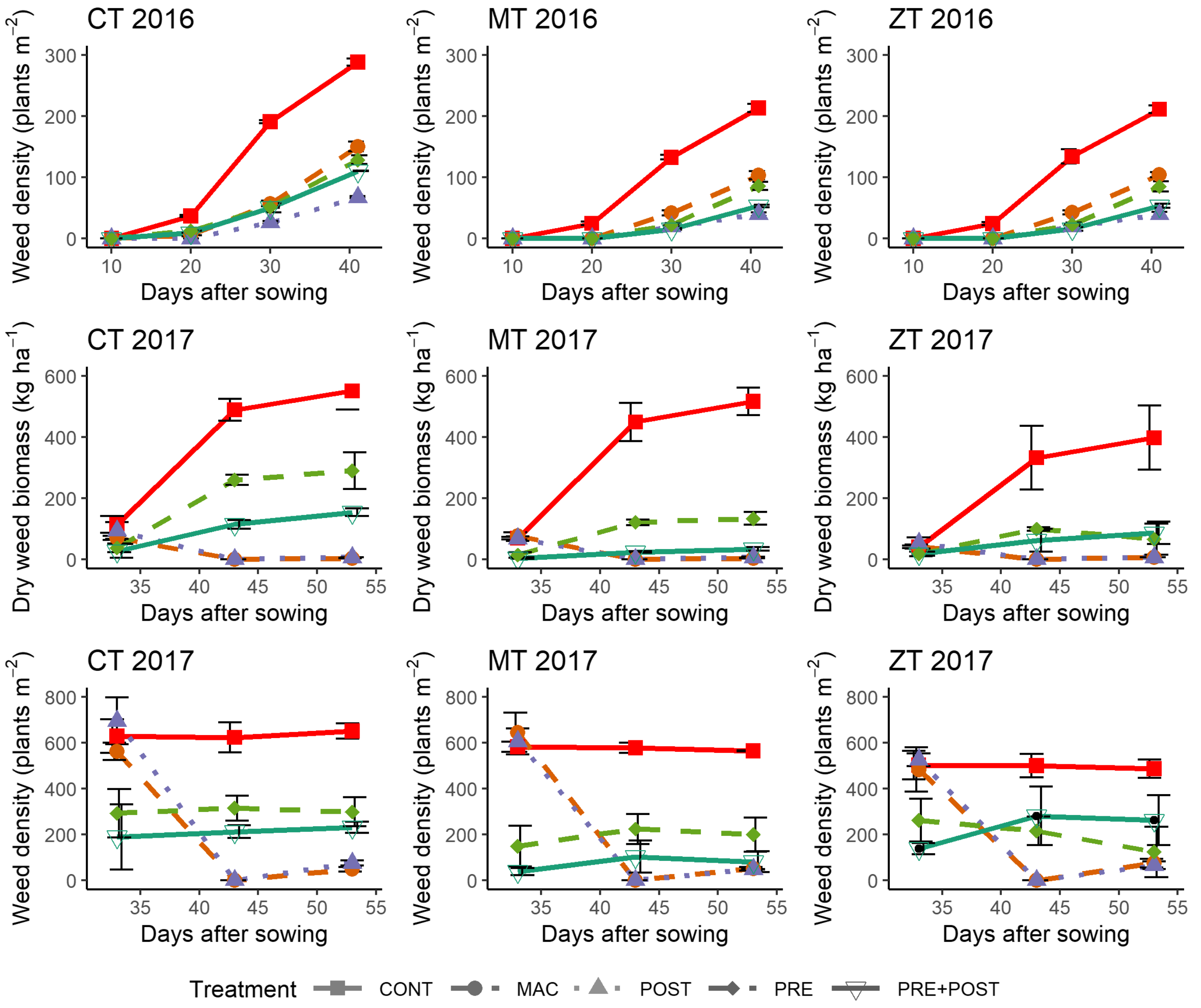

FIGURE 6 Weed biomass and weed density per tillage and treatment in the Papaloapan Region of the state of Oaxaca, Mexico. Weed biomass data not collected at several dates in 2016. Vertical bars indicate standard error. CT: Conventional tillage, MT: Minimum tillage, ZT: Zero tillage, CONT: Control treatment without weed management, MAN: Manual weed management, PRE: Weed management with pre-emergence herbicide, POST: Weed management with post-emergence herbicide, PRE + POST: Weed management with pre- and post-emergence herbicides

yielded about 2.0 t ha^{-1} less than the other treatments. In 2017, weed management treatments gave similar yields under MT, while under CT, PRE yielded 1.4 t ha^{-1} more than CONT. The extra application of post-emergence herbicide in PRE + POST in 2017, or the lower weed control of MAN in 2016 thus did not impact yield. Overall, the lack of effect of weed management treatments on yield indicate that in Valles Centrales weeds are not the main limiting factor to yield.

3.4 | Effect of weed management treatments on productivity

The observed reduction in yield due to weed competition, comparing the highest-yielding weed management treatment to CONT, ranged between 7.7 t ha^{-1} in the Mixteca under ZT in 2017 and 0.4 t ha^{-1} in Valles Centrales under MT in 2017 (Table 3). This means that uncontrolled weeds can reduce maize grain yield from 21% to 92% in Oaxaca, depending on the tillage, weed management, location and year. In the Mixteca, the potential yield reduction was the highest and, correspondingly, all weed management treatments were profitable under all tillage systems; that is, the value of the added yield from controlling weeds was higher than the cost of weed management. In the Mixteca, MAN was more profitable than PRE under ZT and MT in 2016 and more profitable than PRE and PRE + POST under CT, although the most profitable treatment was always POST. In Papaloapan, the return on investment of weed management was lower than in the Mixteca, with only PRE and PRE + POST generating returns over $1000 MXN ha^{-1} under CT. Under ZT and MT, the

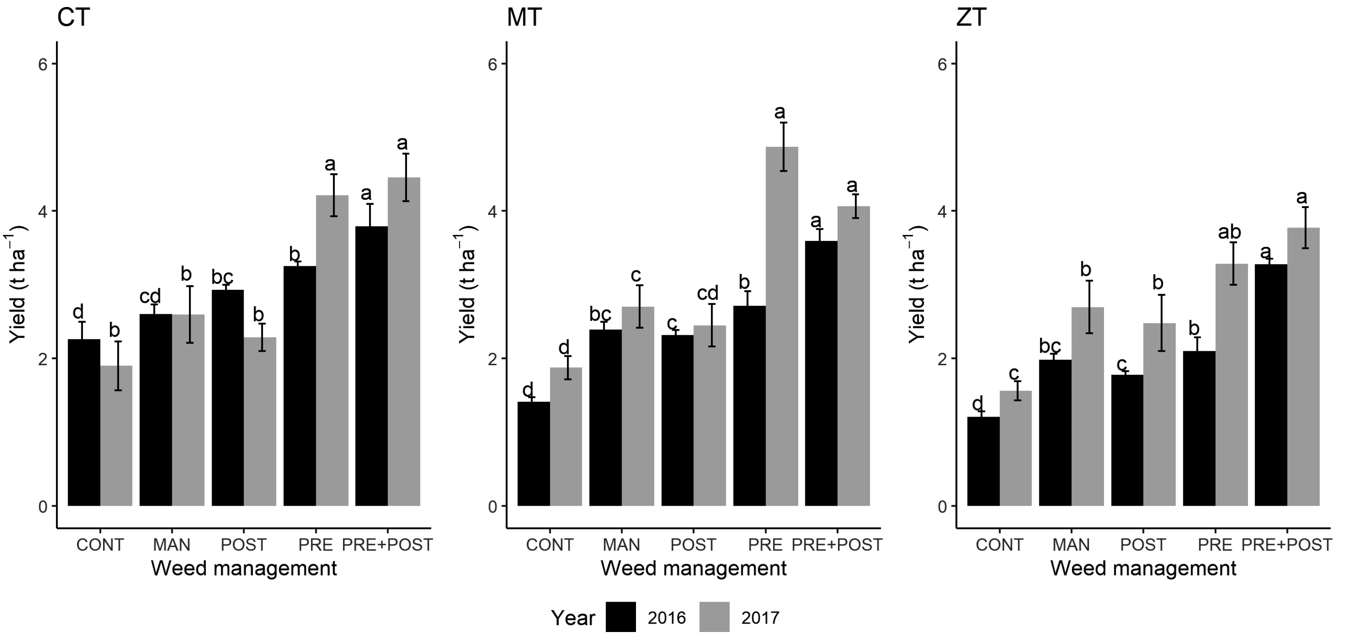

FIGURE 7 Maize yield as a result of weed management treatments in different tillage systems in the trial in the Papaloapan Region of the state of Oaxaca, Mexico. Vertical bars indicate standard error. Treatment means with a common letter are not significantly different in a given year and tillage system at $p < 0.05$. CT: Conventional tillage, MT: Minimum tillage, ZT: Zero tillage, CONT: Control treatment without weed management, MAN: Manual weed management, PRE: Weed management with pre-emergence herbicide, POST: Weed management with post-emergence herbicide, PRE + POST: Weed management with pre- and post-emergence herbicides

return for weed management was higher than under CT, reflecting the greater yield reduction due to weeds in these tillage systems. In Valles Centrales, the benefit of weed management on income was the lowest of all sites, with four weed management treatments even giving negative returns; that is, the value of any added yield was less than the cost of weed management. The return on investment of weed management under CT was especially low, with only PRE + POST and POST generating a positive return in both years. POST was the only treatment that gave positive returns under both CT and MT in Valles Centrales.

4 | DISCUSSION

The effectiveness and profitability of weed management treatments varied between locations and years. In the Mixteca, the growing season is long (approximately 200 days) and a pre-emergence application alone cannot control weeds long enough to avoid yield losses due to weeds (Osorio Alcalá, 2020a). The pre-emergence application used atrazine or atrazine and acetochlor, while the post-emergence application was dicamba and atrazine or foramsulfuron and iodosulfuron. A difference in weed control could thus be related to the different herbicides applied rather than the timing of application. However, we observed good weed control in all cases and MAN had similar results to POST, the effect of the herbicides on yield is thus likely a result of the timing of application more than a difference in weed control between herbicides. The treatments with post-emergence control (POST, PRE + POST and MAN) had higher yields, especially in 2016 and were therefore the most effective in this region. The local weeds are highly competitive with maize and can overshadow it when not controlled, so the return on investment for weed management was highest in the Mixteca.

In the hot, humid Papaloapan, PRE and PRE + POST were the most effective weed management treatments. In this region, both maize and weeds grow quickly and good weed management at the beginning of the growing season is essential. The application of pre-emergence herbicides allowed the maize plants to grow without competition early in the season, so that they later outcompeted weeds. In the other treatments, weeds can establish and, due to their rapid growth, compete heavily with maize. Herbicide treatments were more effective than MAN in suppressing weed density, especially under CT, likely due to the high incidence of narrowleaf weeds at this location.

In Valles Centrales, all four weed management treatments were effective, though not always profitable. Overall, growing conditions in the region are difficult for maize (Osorio Alcalá, 2020a; Ruiz-Vega et al., 2001) and within-treatment variability is high, relative to the overall low yield of 1.6 t ha^{-1} under CT with weed control, on average over both years. The effect of weed management is small in this low-yielding system, as other factors such as soil fertility or water availability likely constitute the main constraints (Fonteyne et al., 2021; Osorio Alcalá, 2020b). The large difference in yield between conventional and minimum tillage in 2016 is indicative of poor and compacted soils. The subsoiling applied in MT reduces compaction and increases water infiltration, so that with weed control yields under MT were 2.5 t ha^{-1} higher than under CT, for which maize yields were on a par with the

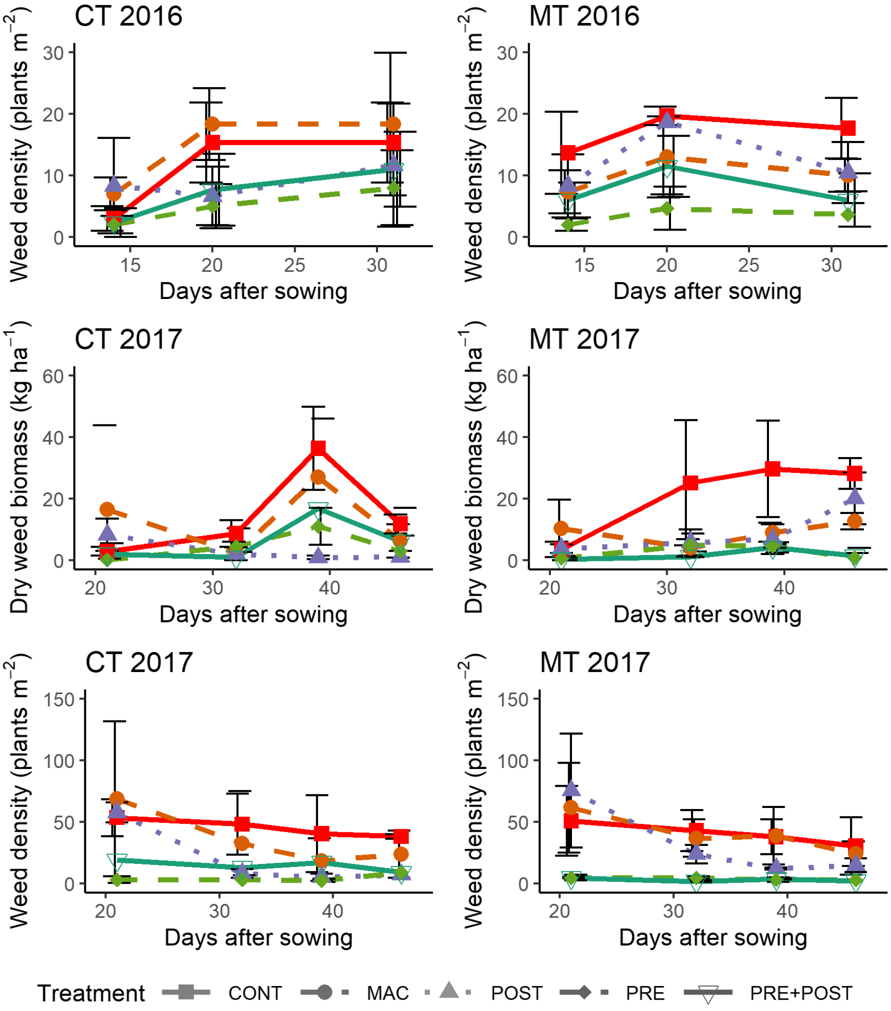

FIGURE 8 Weed biomass and weed density per treatment and tillage system per year in the trial in the Valles Centrales Region of the state of Oaxaca, Mexico. Vertical bars indicate standard error of the measurement. CONT: Control treatment without weed management, MAN: Manual weed management, PRE: Weed management with pre-emergence herbicide, POST: Weed management with post-emergence herbicide, PRE + POST: Weed management with pre- and post-emergence herbicides

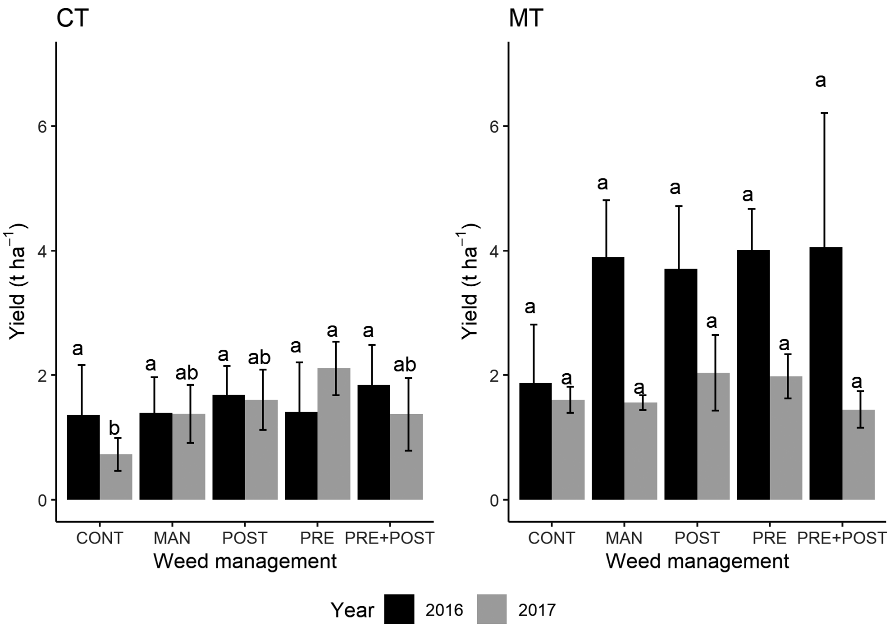

FIGURE 9 Average yield per tillage system × weed management treatment per year in the experiment in the Valles Centrales Region of the state of Oaxaca, Mexico. Vertical bars indicate standard error. Treatment means with a common letter are not significantly different in a given year and tillage system at $p < 0.05$. CT: Conventional tillage, MT: Minimum tillage, CONT: Control treatment without weed management, MAN: Manual weed management, PRE: Weed management with pre-emergence herbicide, POST: Weed management with post-emergence herbicide, PRE + POST: Weed management with pre- and post-emergence herbicides

local average of 0.9 t ha^{-1} (SIAP, 2020). Similarly, a study in Valles Centrales by Osorio Alcalá (2020b) found maize yields of 0.7 t ha^{-1} under CT, compared with 3.5 t ha^{-1} under MT.

Although conservation agriculture is often interpreted as eliminating all tillage, the potential role of mechanical or manual weed management in controlling weeds and creating soil conditions

TABLE 3 Yield difference between highest-yielding treatment with weed management and the control treatment for each location, tillage system and year in t ha^{-1} and % of yield of the highest-yielding treatment; added income in $ MXN ha^{-1} due to weed management per site, year and treatment, compared to the control treatment, calculated as income due to higher grain yield minus the cost of weed management

	Mixteca		Papaloapan		Valles Centrales	
	2016	**2017**	**2016**	**2017**	**2016**	**2017**
Maximum yield reduction (t ha^{-1})						
ZT	5	7.7	2.1	2.2	NA	NA
MT	6.5	7.4	2.2	3	2.2	0.4
CT	3.2	4.3	1.5	2.6	0.5	1.4
Maximum yield reduction (%)						
ZT	92	79	63	59	NA	NA
MT	85	77	61	62	54	21
CT	48	47	40	57	26	65
Added income of weed management ZT ($MXN ha^{-1})						
MAN	$21 294	$27 624	$1662	$2642	NA	NA
PRE + POST	$21 749	$32 638	$8563	$6594	NA	NA
POST	$23 985	$32 302	$1142	$1897	NA	NA
PRE	$5404	$27 214	$2992	$5135	NA	NA
Added income of weed management MT ($MXN ha^{-1})						
MAN	$27 247	$27 211	$2687	$1407	$11 634	**$−1695**
PRE + POST	$27 497	$26 145	$9100	$6492	$11 452	**$−3171**
POST	$31 257	$32 076	$2815	$511	$ 9852	$1066
PRE	$17 209	$32 147	$5044	$10 214	$11 209	$1098
Added income of weed management CT ($MXN ha^{-1})						
MAN	$9732	$14 893	**$−518**	$889	**$−277**	$ 2491
PRE + POST	$9595	$11 560	$5846	$7947	$1286	$1625
POST	$14 930	$18 048	$1635	**$−240**	$808	$3723
PRE	$8094	$12 569	$3498	$7485	**$−1341**	$7108

Abbreviations: CONT, Control treatment without weed management; CT, Conventional tillage; MAN, Manual weed management; MT, Minimum tillage; NA, not available; POST, Weed management with post-emergence herbicide; PRE, Weed management with pre-emergence herbicide; PRE + POST, Weed management with pre- and post-emergence herbicides; ZT, Zero tillage.

conducive to high yielding maize should not be ignored (Bajwa, 2014; Lee and Thierfelder, 2017). At all sites, weed incidence for CONT was less under CT, as inversion tillage controls weeds early in the season, whereas under ZT, they are not controlled by tillage. In our study, manual weed management gave results similar to those of applying herbicide post-emergence. This has also been observed in similar studies (Hanson and Smith, 1992; Imoloame, 2017; Muoni et al., 2013) and highlights the potential of manual or mechanical weed management as an effective alternative to herbicide use. The cost of manual control was also comparable to that for the use of herbicides. Field labour has become more scarce and costly in recent years, a circumstance observed in other studies of conservation agriculture in smallholder settings, which would make manual controls more expensive (Muoni et al., 2013). Hybrid systems of shallow between-row cultivation and herbicide applications or hand weeding on the rows could also reduce herbicide use and costs and, accordingly, help to avoid the development of herbicide resistance in weeds. All fields were under CT before the experiment started, and thus had weeds associated to CT. In the long term, conservation agriculture can shift weed communities and reduce weed problems (Derrouch et al., 2021; Fonteyne et al., 2020), which could make manual or mechanical control of weeds more economical, but can also require changes in weed management with the changes in weed species. Our study did not evaluate weed management under 'full' conservation agriculture, given the impossibility of practicing crop rotations in the short timeframe, but such rotations have been shown to reduce weeds (Blackshaw, 1994; Fonteyne et al., 2020), although the use of commonly applied herbicides for different crops in the same field over years might have undesirable residual effects (Muoni et al., 2014).

Our findings suggest the most effective weed management methods for the regions studied, but in the field, a flexible approach should be used, applying pre- and post-emergence herbicides and manual controls as is most suited for each case. For example, in Papaloapan, in both years and in Valles Centrales in 2016, weed density was low in the PRE + POST treatment, and it was considered unnecessary to apply the post-emergence application. Significant differences in weed density or biomass did not necessarily result in higher yields or improved profitability, showing that absolute weed control is not required. No single best option for weed management was found across sites or tillage systems. There are few studies on tillage-weed management interactions (Streit et al., 2003); more research is needed to determine the most effective weed management methods for diverse production systems across Mexico (Nichols et al., 2015) and non-chemical methods should not be overlooked. Some of the active ingredients used in our study are not allowed for use in the European Union and parts of the United States, specifically atrazine, acetochlor and glufosinate and may also be prohibited in Mexico in the near future. The results of our study should, however, not be interpreted in light of the effectiveness of the specific active ingredients, but rather in terms of the weed management strategies. For all the used active ingredients alternatives that can achieve similar levels of control exist, which could be used instead. Furthermore, our study only evaluated weed management and tillage, while many other factors such as crop rotation, mulching, varieties can also have an impact on weed incidence and yield and should be considered in a holistic weed management program (Maclaren et al., 2020). The capacity of farm advisors and farmers to interpret different circumstances and correctly adjust weed management to field conditions is critical; related research and capacity development are in order.

MT was numerically the highest-yielding tillage system across all three sites; however, the study did not have replicates of the tillage systems at each site. Conversely, ZT generally resulted in higher weed pressure and lower yields in this early transition period away from CT, which had been the baseline pre-treatment at all locations. The study only lasted 2 years and yields of rainfed maize are often lower when switching from CT to ZT (Pittelkow et al., 2015), at least in the first couple of years. In the long term, maize under ZT can yield about as much as under MT, in the Mixteca (Osorio Alcalá, 2020b). Research in Papaloapan has shown that maize under ZT and CT gives similar yields in the long run, although conservation agriculture can increase maize yields if it is implemented using permanent raised beds, a method of minimum tillage in which only the furrows are reshaped before planting (Núñez Peñaloza and Villa Alcántara, 2020; Saldivia-Tejeda et al., 2021). The higher yields and lower weed pressure associated with MT indicates that moderate intensity soil disturbance may optimise maize yields in Oaxaca, at least in the short term. In the long term, soil conservation, reduced environmental impact and increased yield point to conservation agriculture as the desirable option (Fonteyne et al., 2021; Lal, 2015; Wall et al., 2020), however, in Oaxaca the yield reduction in the first years may currently limit farmer adoption.

Further research is necessary to determine the optimum level of tillage in each region. Depending on local conditions, zero tillage or a form of minimum tillage such as vertical tillage or permanent raised beds performs better, or it may be necessary to practice minimum tillage in the first growing seasons to prepare the terrain for the successful implementation of conservation agriculture (Fonteyne et al., 2021). Experience in other regions of Mexico indicates that the short-term problems of conservation agriculture may be resolved by adaptive research, increasing adoption (Martinez-Cruz et al., 2019; Monjardino et al., 2021). In our study, adequate weed management was more critical to achieve optimum yields in ZT; however, in all regions, the best performing treatments effectively managed weeds in all tillage systems. The implementation of ZT must be supported by adaptive research to determine the best accompanying management practices for the local conditions. Given that the best weed management practices were similar between tillage systems, an approach of mother–baby trials with replicated on-station trials and on-farm validation of the best weed management treatment under a single tillage system may thus be a more efficient approach than the experiments performed for our study.

5 | CONCLUSIONS

Efficacy and efficiency of weed management methods varied significantly across locations and years in our study, as influenced by local agro-ecological conditions. Weed pressure and economic returns to weed management were generally higher in minimum and zero tillage relative to conventional tillage, though we cannot draw definitive conclusions about tillage systems in this study. In the temperate location of the Mixteca, post-emergence herbicide applications were most important, while in hot and humid Papaloapan, pre-emergence applications were crucial. In the semi-arid Valles Centrales, there was no difference among weed management methods, as all had minor effects on maize yield. Weeds can significantly reduce maize yields in the Mixteca, whereas they are not the main constraint in Valles Centrales. Adequate weed management could be achieved under all tillage systems at all locations, though the economic benefit of weed management was greatest under reduced tillage (minimum or zero tillage). The most effective treatments at each site could control weeds under minimum and zero tillage to a similar level as under conventional tillage, weed management should therefore not be a limiting factor to introducing reduced tillage and, thereby, conserve soils in Oaxaca.

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CONFLICT OF 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.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/wre.12530.

DATA AVAILABILITY STATEMENT

The data are available at DataVerse: Verhulst, N., Fonteyne, S., Leal Gonzalez, A.J., 2021, "Weed management by tillage by site interaction experiment in Oaxaca, Mexico", https://hdl.handle.net/11529/10548568, CIMMYT Research Data & Software Repository Network, V1, UNF:6:hu0qohjWI53q6ZnI87Pexg== [fileUNF].

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