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RESEARCH ARTICLE

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Effects of conservation agriculture on physicochemical soil health in 20 maize-based trials in different agro-ecological regions across Mexico

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Abstract

Maize (*Zea mays* L.) is Mexico's primary staple food, but the Country's degrading soils and climate variability limit its productivity. Conservation agriculture (CA), a management technique that combines minimal tillage, permanent soil cover, and crop diversification, could reduce soil degradation and help improve soil health. There is however a lack of information about the effects of CA on soil health in the diverse agroecological conditions in Mexico. This study reports results of a field trial network established to adapt CA to Mexico's diverse cropping systems and local conditions. Physicochemical soil health, also referred to as soil quality, was studied in 20 trials in agro-ecologies ranging from handplanted traditional systems to intensive irrigated systems, initiated between 1991 and 2016. Soil in CA was compared to the local conventional practice (CP), which commonly involves tillage, residue removal, and continuous maize production. Across the sites, organic matter and nitrates were higher in the top (0–5 cm) layer of soil and soil aggregate stability was greater under CA than under CPs. For other soil health parameters, such as nutrient content, pH or penetration resistance, the effects of management varied widely across sites and soil types

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and most were determined more by local soil type than by management. CA increased maize yields at most sites and on average by 0.85 ± 1.80 t ha^{-1}. Given the significant variation across agro-ecologies, local adaptive trials are important to assess the effects of CA on soil health and fit the practice to local conditions.

KEYWORDS
crop rotation, no till, soil cover, soil quality, soil organic matter

1 | INTRODUCTION

Maize (*Zea mays* L.) is the staple food of Mexico and a cultural symbol as well as a source of food, feed, and income for smallholder farm communities, however, its production perennially falls short of domestic demand (Govaerts et al., 2019). Mexico is a diverse country with many different soil types, climates and crop and livestock production systems. Maize is grown from sea level to 3,000 m altitude, from semi-desertic conditions to tropical rainforests, and in ancient multicropping systems and under large-scale irrigated production. The crop's productivity in Mexico is typically limited by degraded soils, water scarcity, and cropping practices and, increasingly, climate change (Hernandez-Ochoa et al., 2018; SEMARNAT, 2016). Mexico's broad agro-ecological diversity offers an opportunity to study the effects of conservation agriculture (CA) on maize productivity and soil health in many different conditions and production systems.

CA is a production system based on minimal tillage (zero tillage (no-tillage), or reduced tillage or cropping on permanent raised beds), maintaining a permanent soil cover (crop residues, a living crop, or a cover crop) and crop diversification (crop rotations, intercrops, or relay cropping). Many studies about CA, especially meta-analyses, report on zero tillage with or without residues (Krupnik et al., 2019) but this study refers to CA specifically as production systems that simultaneously include minimal tillage, a permanent soil cover, and crop diversification.

Implementation of CA could help improve the productivity of maize in Mexico by reducing land degradation and improving soil health, given the successful results of implementing CA in other countries (Wall, Thierfelder, Hobbs, Hellin, & Govaerts, 2020). Soil health can be understood as "….the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans" (Norris et al., 2020) and depends on the biological, chemical and physical processes in the soil. Often, CA increases soil carbon (C) stocks, though this might frequently be a result of redistribution of C to the surface rather than an increase in total C (Govaerts et al., 2009; Powlson, Stirling, Thierfelder, White, & Jat, 2016). CA can improve physical soil characteristics, such as soil penetration resistance and aggregate stability (Fuentes et al., 2009; Lichter et al., 2008; Verhulst et al., 2011), which can improve infiltration and aeration and reduce erosion (Lanckriet et al., 2012) and nutrient loss. Nutrient cycles can also be impacted by CA, but little is understood about the nitrogen (N) cycle under CA (Grahmann, Dittert, Verhulst, Govaerts, & Buerkert, 2019) or the cycles of phosphorus (P), potassium (K), or micronutrients (Ranaivoson et al., 2017). Residue retention can enhance nutrient cycling but also lead to nutrient immobilization and stratification (Turmel, Speratti, Baudron, Verhulst, & Govaerts, 2015). There could be a publication bias, whereby the results of field trials with significant effects of CA are more likely to get published than studies involving sites where there are no significant effects, which may lead to an overestimation of the positive effects of CA in the published literature.

The soil health effects of CA vary significantly between sites, depending on local conditions like soil type, production system, or climate (Bai et al., 2018; Palm, Blanco-Canqui, DeClerck, Gatere, & Grace, 2014); however, most data on soil health in CA have been collected in single-site experiments, which means the same environmental conditions, soil, and climate. Differences in sampling methodologies can generate considerable differences in research outcomes, especially when comparing different types of tillage (Powlson et al., 2016), that make it difficult to compare results among different studies. It is therefore necessary to measure soil health in a large number of sites with variable environmental conditions, using a standardized methodology in order to be able to draw more valid conclusions (Palm et al., 2014).

Although CA everywhere involves the same three components, how they are implemented depends on local conditions (Williams et al., 2018). If the components of CA are not adapted to local conditions, adoption of the system by farmers is unlikely. With this in mind, in 2011 CIMMYT set up a network of 'research platforms' across Mexico in collaboration with local partners, such as research institutes, universities, farmers' organizations, and extension agencies. The network aims to adapt CA-based farming methods to local productions systems, demonstrating the best results to farmers and training farmers and farm advisors in their use (Fonteyne & Verhulst, 2017; Van Loon et al., 2020). These sites encompass diverse farm settings, ranging from intensive and productive irrigated systems, to rain-fed mechanized production and traditional hand-planted, multicrop, subsistence farming. Targeted to local conditions and featuring a control treatment that represents the local conventional practice (CP) plus several CA-based options designed with the constraints of local farmers in mind.

This study compared chemical and physical soil health under CA and CP at 20 research platforms where treatments had been in place for at least 3 years, using a standardized methodology, with the aim of evaluating the hypothesis that CA improves soil health in a broad range of agro-ecological conditions.

2 | MATERIALS AND METHODS

2.1 | Experiments and treatments

Soil samples were taken at the end of the 2018 maize growing season (Table S1) at 20 research platforms in the network managed by CIMMYT, that had treatments in place for at least three years, representing diverse maize production systems across South and Central Mexico (Figure 1 and Table 1). Each research platform has a set of treatments that evaluates potentially more sustainable agronomic practices than the CP of the region. All platforms have a randomized complete block design with two to four repetitions. Two repetitions were used for soil sampling at each site, to sample the maximum number of sites within the available budget while still being able to perform statistical analyses. The plot size at each site depends on local conditions, in regions with large-scale commercial agriculture, plot size is large, for example, 450 m^2 in San Martin Hidalgo, Jalisco, while in regions with small-scale agriculture, plots are smaller, for example, 48 m^2 in San Miguel Tlacamama, Oaxaca.

The soil samples came from the CP treatments, which represent the local production system, and a CA treatment selected according to these criteria: (a) it included all three components of CA (minimal tillage, soil cover and crop diversification), (b) it had the same fertilization as the CP, and (c) if several treatments met this criteria, of these treatments, the treatment with the highest yield in the last 3 years was selected, to represent the CA practice recommended to farmers (Table 2). The CP

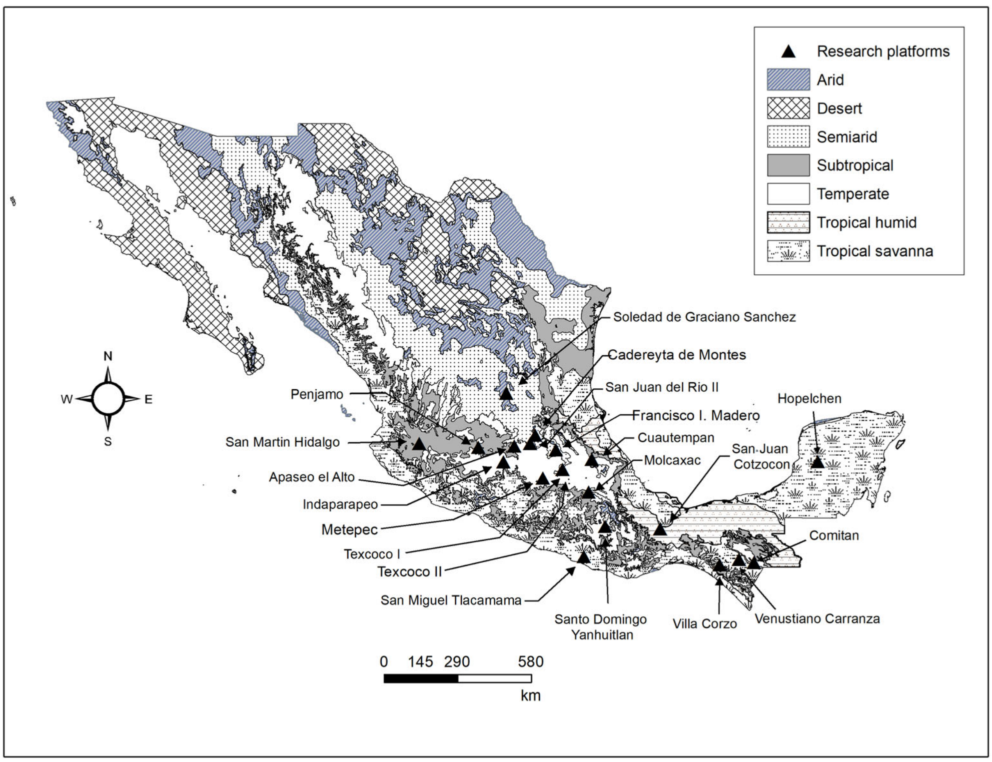

FIGURE 1 Location in Mexico of the trials included in the study. Texcoco I and II are located on the same research station [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Description of the sites included in the study

Site name (Municipality)[a]	State	First year	Latitude (North)	Longitude (West)	Altitude (masl)	Institution managing experiment	Growing cycle[b]	Water regime	Climate (Koppen classification)
Apaseo el Alto	Guanajuato	2014	20.3603	100.5672	1,956	Tecnológico Nacional de México/Instituto Tecnológico de Roque	Summer	Rainfed	Cwb
Cadereyta de Montes	Querétaro	2015	20.7493	99.8228	2,000	Sustentabilidad Agropecuaria Queretaro	Summer	Rainfed	Bsk
Comitán de Domínguez	Chiapas	2014	16.2272	92.0806	1,558	Tecnológico Nacional de México/Instituto Tecnológico de Comitán	Summer	Rainfed	Aw
Cuautempan	Puebla	2015	19.8879	97.8182	1,613	Unión Rural de Productores de Cuautempan y Tetela	Summer	Rainfed	Cfb
Francisco I. Madero	Hidalgo	2011	20.2301	99.0898	1,998	Universidad Politécnica de Francisco I. Madero	Summer and winter	Irrigated	BSk
Hopelchén	Campeche	2016	19.8071	89.8111	87	Agroenlace Campeche	Summer	Rainfed	Aw
Indaparapeo	Michoacán	2012	19.7972	100.9513	1,888	RED_INNOVAC	Summer	Rainfed	Cwb
Metepec	México	2014	19.2271	99.5505	2,640	Centro Internacional de Mejoramiento de Maíz y Trigo	Summer	Rainfed	Cwb
Molcaxac	Puebla	2011	18.7265	97.9272	1,830	Centro de Bachillerato Tecnológico Agropecuario No. 305	Summer	Rainfed	Cwb
Pénjamo	Guanajuato	2015	20.3142	101.8366	1,690	Independent consultant	Summer and winter	Irrigated	Cwa
San Juan Cotzocón	Oaxaca	2014	17.4253	95.3980	123	Unión de Productores Agrícolas y Pecuarios de Cotzocón	Summer	Rainfed	Aw
San Juan del Río	Querétaro	2012	20.4553	100.0033	1,900	Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias	Summer and winter	Irrigated	Cwb
San Martín Hidalgo	Jalisco	2015	20.4489	103.9373	1,304	ASSUJAL	Summer	Rainfed	Cwa
San Miguel Tlacamama	Oaxaca	2015	16.4464	98.0960	265	Universidad Autónoma Chapingo	Summer	Rainfed	Aw
Santo Domingo Yanhuitlán	Oaxaca	2012	17.5081	97.3508	2,138	Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias	Summer	Rainfed	Cwb
Soledad de Graciano Sánchez	San Luis Potosí	1995	22.2276	100.8495	1,835	Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias	Summer and winter	Irrigated	BSk
Texcoco I	México	1991	19.5297	98.8527	2,240	Centro Internacional de Mejoramiento de Maíz y Trigo	Summer	Rainfed	Cwb
Texcoco II	México	1999	19.5297	98.8527	2,240	Centro Internacional de Mejoramiento de Maíz y Trigo	Summer	Rainfed	Cwb
Venustiano Carranza	Chiapas	2016	16.3454	92.6037	597	Servicios Integrales De Asesoría Externa Profesional	Summer	Rainfed	Aw
Villa Corzo	Chiapas	2016	16.1577	93.2918	596	Independent consultant	Summer	Rainfed	Aw

[a]Two sites were used in Texcoco, they are distinguished with roman numerals
[b]There are two main growing cycles in Mexico: spring-summer from May to December and fall-winter from October to May; the duration of these cycles varies with region, crop, and weather

TABLE 2 Crop rotation, tillage, and residue management of the conventional and conservation agriculture treatment and the fertilization and soil type per site

Site name	Conventional practice treatment	Conservation agriculture treatment	Fertilization[a] (NPK, kg ha^{-1})	Soil type
Apaseo el Alto	M-M, Conv Beds, Rem	M-Be, Broad Perm Beds, Keep	100-80-60 + Micro	Vertisol
Cadereyta de Montes	M-M, Conv Beds, Rem	M-Be, Broad Perm Beds, Keep	70-30-15	Vertisol
Comitán de Domínguez	M-M, Conv Beds, Rem	M/Ca, Perm Beds, Remove	59-48-0 15 S	Planosol
Cuautempan	M-M, Conv, Rem	M-P, Zero Till, Keep	92-00-00	Luvisol
Francisco I. Madero	M-O, Conv, Rem	M-O, Zero Till, Keep	42-0-0 + Micro + Irrigation with blackwater	Vertisol
Hopelchén	M-M, Conv, Keep	M-Sy, Zero Till, Keep	120-55-40	Lixisol
Indaparapeo	M-M, Conv, Keep	M-M, Broad Perm Beds, Keep	196-46-60 + Micro	Vertisol
Metepec	M-M, Conv, Rem	M-Tr, Perm Beds, Keep	150-46-60	Phaeozem
Molcaxac	M-M, Conv, Keep	M-Be, Perm Beds, Keep	72-23-00 +1.5 t ha^{-1} manure	Leptosol
Pénjamo	M-W, Broad Conv Beds, Keep	M-W, Broad Perm Beds, Keep	390-105-50-10 Zn	Vertisol
San Juan Cotzocón	M-M, Conv, Partial	M/Be, Perm Beds, Keep	92-60-00 + 10.2 Mg + 15.3 Ca	Luvisol
San Juan del Río	M-Ba, Conv, Rem	M-Ba, Zero Till, Partial	280-60-30	Phaeozem
San Martín Hidalgo	M-M, Conv, Keep	M-M, Zero Till, Keep	198-30-30 + Micro	Vertisol
San Miguel Tlacamama	M-M, Zero Till, Rem	M//C, Zero Till, Keep	0 (*Mucuna pruriens* cover crop)	Luvisol
Santo Domingo Yanhuitlán	M-M, Conv, Rem	M-Be, Perm Beds, Keep	160-40-60-10 Mg	Vertisol
Soledad de Graciano Sánchez	M-O, Broad Conv Beds, Rem	M-O, Perm Beds, Partial	200-100-00-10 Mg-44 Fe-2 Bo	Durisol
Texcoco I	M-M, Conv, Rem	M-W, Zero Till, Keep	150-40-0	Phaeozem
Texcoco II	M-W, Conv Beds, Keep	M-W, Perm Beds, Keep	150-40-0	Phaeozem
Venustiano Carranza	M-M, Conv, Rem	M/Sq, Perm Beds, Keep	130.5-46-60	Phaeozem
Villa Corzo	M-M, Conv, Rem	M/D, Zero Till, Partial	160-46-60	Regosol

[a]Fertilization applied in last cropping cycle before sampling. Fertilization may have changed over the course of the years, especially in the oldest trials. Micro indicates a commercial or homemade mixture of micronutrients was applied but the exact content was not reported or known.
Abbreviations: Rotation: M: maize, Ba: barley (*Hordeum vulgare* L.), O: fodder oats (*Avena sativa* L.), Tr: triticale (x *Triticosecale* Wittm. ex A. Camus), Be: beans (*Phaseolus vulgaris* L.), Ca: *Canavalia* sp., D: *Dolichos sp*., Sq: squash (*Cucurbita* spp.), W: wheat (*Triticum durum* L. or *Triticum aestivum* L.), C: cowpea (*Vigna unguiculata* (L.) Walp), M-P: maize-pea, Sy: soy (*Glycine max* (L.) Merr.); Cycling crops: -, relay cropping: /, polyculture: //; Conv: Conventional tillage, Conv beds: Raised beds with conventional tillage (one maize row, approximately 0.75-0.8 m wide), Broad Conv beds: Broad (two maize rows, approximately 1.6 m wide) raised beds witch conventional tillage, Perm Beds: Permanent raised beds (one maize row, approximately 0.75-0.8 m wide),, Broad Perm Beds: Broad Permanent raised beds, Zero Till: Zero tillage; Residue Management: Rem: Remove all, Keep: Keep all in the field, Partial: Remove part of the residue (50–75%).

treatments represent local practices in sowing density, sowing time, crop variety, tillage, residue management, crop rotation, and fertilization. Management factors such as fertilization, weed management, and pest management were the same for all treatments at each site. They may differ somewhat from the local practice in some locations, especially at sites in regions where management is generally deficient.

The CP treatments always evaluated maize, with four of the sites having two crop cycles per year, growing maize in the summer and a small grain cereal in the winter (Table 2). Conventional tillage is generally done by disk-plowing and disc-harrowing, with raised beds then formed in many cases. At San Miguel Tlacamama, the CP involves burning residues followed by maize monoculture, with no tillage. In many regions, residues are removed for fodder or burned, which is reflected in the CP treatments at 14 sites. The CA treatments included crop rotations with maize every other year, crop rotations with maize in summer and another crop in winter, and relay or multicrops. In two platforms, Indaparapeo and San Martin Hidalgo, an economically viable rotation crop could not be identified so there was no rotation in the CA treatment. The CA treatments were either sown directly on the flat (zero tillage) or in permanent raised beds formed at the beginning of the experiment and not tilled thereafter, with the only soil movement being the reshaping of the furrows. In CA, soil cover was assured by leaving all or part of crop residues (the latter, where residues are in high demand as fodder) on the field after harvest, except in Comitán, where a Canavalia cover crop was used (Table 2).

Data on soil type were provided by the site manager or retrieved from the soil map of the Mexican National Statistics and Geography Institute (INEGI, 2020).

2.2 | Soil sampling and analysis

Soil from the selected treatments was sampled in two repetitions per site at 0 to 5 cm and 5 to 30 cm depth, in five points per plot and a composite sample made. Samples were taken in the middle of the bed, close to the sowing line. The 0–5 cm sample was taken with a small shovel and separated in an undisturbed sample for aggregate analysis at CIMMYT and a disturbed sample that was air-dried and sent to the soil laboratory Fertilab in Celaya, Mexico, where all other analyses were done. Samples were taken in treatments with a maize crop in the preceding cropping cycle, after it reached physiological maturity and before a new crop was planted. Samples for Soledad de Graciano Sánchez were originally taken for another study following the same sampling protocol; therefore, the CP and best CA treatment were selected from Fonteyne, Martinez Gamiño, Saldivia Tejeda, and Verhulst (2019) and included in the database for this study.

Phosphorous concentration was determined according to Bray and Kurt as described in Gavlak, Horneck, Miller, and Kotuby-Amacher (2003) and according to Olsen et al. (1954). Interchangeable bases (Ca, Mg, Na, and K) were determined with the ammonium acetate method, micronutrients (B, Cu, Mn, Fe, Zn) were determined with the DTPA-Sorbitol method at pH 7, and organic matter concentration was determined according to the Walkley-Black titration method as described in Gavlak et al. (2003). Sulfur was determined with the turbidimetric method (Gavlak et al., 2003) and nitrates with the colorimetric method as described in Etchevers-Barra et al. (2000). Soil texture was determined using the Bouyoucos method, electrical conductivity (EC) using an electrode, and Al^{3+} and H^+ concentrations using the potassium chloride method; all three as described in SEMARNAT (2002). Penetration resistance and direct infiltration were measured when the necessary equipment was locally available; this was possible in 15 sites (Table S1).

Aggregate distribution and aggregate stability were determined by dry and wet sieving. Before the analysis, samples were sieved with an 8 mm mesh sieve and aggregates larger than 8 mm were broken up. For dry sieving, samples were then sieved with sieves having mesh sizes of 4, 2, 1, 0.5, 0.25, and 0.053 mm, while for wet sieving samples were moistened first in deionized water for 20 min and then sieved with the meshes of the same sizes. All fractions were then oven dried, sand correction was applied and mean weight diameter (MWD) was calculated, as described in (CIMMYT, 2013b, 2013c). Penetration resistance was measured with a dynamic penetrometer at depths of 0–15, 15–30, 30–45, and 45–60 cm as described in (CIMMYT, 2013a). Infiltration was measured as direct surface infiltration by the 'time to pond' method as described in Govaerts, Sayre, and Deckers (2006). This method determines the time it takes for water poured with a watering can on an area marked by a wire ring to start flowing out of ring, as a measure of direct infiltration rate.

2.3 | Maize yield data collection

Maize grain yield was measured in the same 2018 growing season as when soil samples were taken by harvesting all cobs in a specified representative plot area; it was reported at 14% moisture content, the common practice in Mexico, with grain moisture determined either using a grain moisture meter or by oven-drying a subsample.

2.4 | Statistical analysis

All statistical analyses were performed in R version 3.6.0 (R Core Team, 2020). Chemical soil data were first analyzed on a general level with the model:

$$Y_{ijkl} = m + T_i + D_j + T * D_{ij} + S_k + R(S)_{lk} + error_{ijkl}$$

Where: Y is the response variable, m is the overall mean, T are the effects of the factor 'Tillage system' (CA or CP), D are the effects of sampling depths (0–5 cm or 5–30 cm), S are the site effects, and R are the repetition effects within a site. Repetition and site were considered as independent random factors with zero means and some variance. The model was analyzed using the *glm* and *aov* functions from the STATS package which perform a generalized linear model and ANOVA. Thereafter variables were evaluated with the same method for each site separately. Given the large variation between sites and treatments in parameter values and the many comparisons, the choice was made to include illustrative figures and provide the results of the statistical analysis in Table S2. Correlations between parameters were calculated using the *cor* function from the STATS package which calculates Pearson's correlation coefficient (R Core Team, 2020), and principal components analysis to describe the correlation matrix to discover similarities or differences between CA and CP observations across all measured parameters. This was done to simplify the interpretation of the results without compromising it. Parameters measured at 0–5 and 5–30 cm clustered together, therefore the analysis was performed only using parameters measured in the 0–5 cm layers, as these were the most distinct between crop management systems. PCA was calculated with the *PCA* function from the FACTORMINER package (Lê, Josse, & Husson, 2008), with missing data imputed using the *imputePCA* function of the MISSMDA package. As CA and CP observations did not cluster separately, but rather per site and soil type, PCA was performed on the CA and CP observations separately, and both PCAs were compared using Procrustes analysis (using the *procrustes* function from the VEGAN package) to determine which parameters of the first two components differed most between CA and CP.

3 | RESULTS

3.1 | Chemical soil health indicators

Soil organic matter (SOM) content was significantly different between CA and CP over all sites. In the 0–5 cm layer, SOM was on average 31% higher (0.91% SOM) under CA. SOM was, on average 11% higher (0.25% OM) in the 5–30 cm layer, though not significantly over all sites (Figure 2a). On a site basis, SOM was significantly higher in the 0–5 cm layer at the Cuautempan, Indaparapeo, Santo Domingo Yanhuitlán, and Texcoco I, (p < 0.05), and Metepec, San Juan del Rio, Soledad de Graciano Sánchez, and Texcoco II, at p < 0.08. In the 5–30 cm layer, SOM was only significantly higher in Santo Domingo

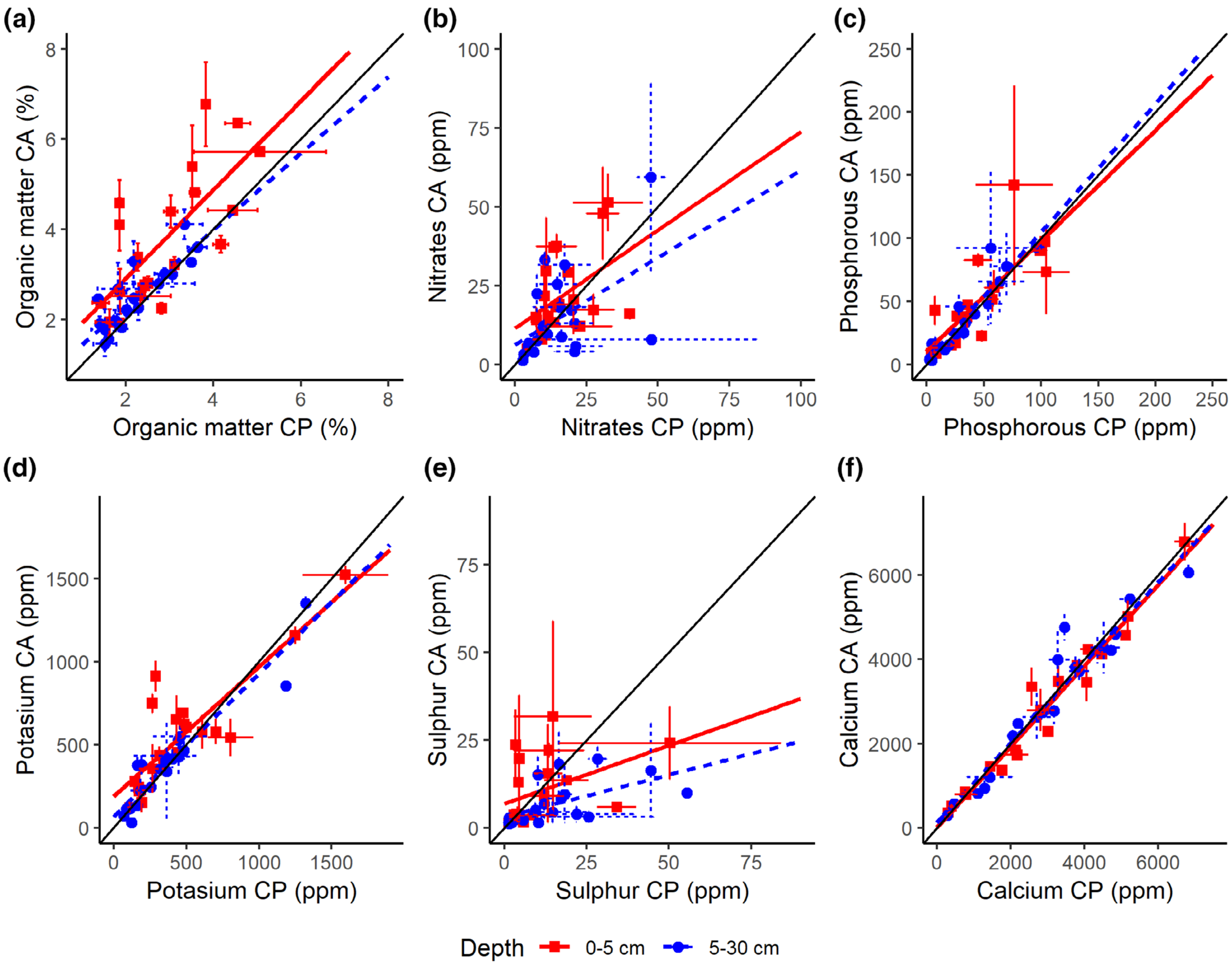

FIGURE 2 Scatter plots of soil organic matter and nitrate, phosphorous, potassium, sulfur, and calcium concentrations in the 0–5 cm (red) and 5–30 cm (blue) layers. Points indicate the sites, with Conventional practices (CP) treatments represented on the x-axis and the corresponding conservation agriculture (CA) treatments represented on the y-axis. Error bars indicate standard error. The black line indicates the 1:1 relationship, dots above this line are higher in CA, while points below this line are higher in CP. The regression lines are illustrative of the general deviation from the 1:1 relation and do not indicate a regression model [Colour figure can be viewed at wileyonlinelibrary.com]

Yanhuitlán. The sites where SOM is different tend to be the sites in the study that have been under CA for the longest time, except for Cuautempan, which were initiated in 2016 (Figure S1).

On average, macronutrient concentrations were higher in CA than in CP treatments in the 0–5 cm layer, while the nitrate, P, and K concentrations in the 5–30 cm layer were similar (Figure 2b–d). These differences were not significant over all sites, except for the significantly higher nitrate concentration in CA in the 0–5 cm layer. Nitrate concentrations were significantly higher in CA in the 0–5 cm layer in Texcoco I, Cuautempan, and San Juan Cotzocón, and in the 5–30 cm layer in Cadereyta and Comitán. P was only significantly higher in CA in both layers at Soledad de Graciano Sanchez. K was significantly higher in CA in the 0–5 cm layer at Texcoco I, Texcoco II, and Santo Domingo Yanhuitlán, and in the 5–30 cm layer at Santo Domingo Yanhuitlán and significantly lower in the 5–30 cm layer at Comitán and Soledad de Graciano Sanchez. Differences in nutrient concentration were not related to fertilization, except for K, where significant differences were only observed in the absence of K fertilization.

The concentrations of other nutrients did not generally differ between CP and CA, except for S, but there were 22 significant differences at individual sites. Sulfur was the macronutrient showing the largest differences between CA and CP, with significantly higher concentrations under CA; 49% higher on average in the 0–5 cm layer and 33% lower in the 5–30 cm layer. Sulfur varied widely between sites, from 1 ppm in CA in 0–5 cm at Cadereyta, Metepec, and Santo Domingo Yanhuitlán, to 55 ppm at San Martin Hidalgo under CP in the 5–30 cm layer. In contrast with macronutrients, there was no general trend to higher micronutrient levels in in CA in the 0–5 cm layer (Figure 3a–f).

Concentrations of Zn, Fe, and Mn were on average over 30% higher in CA in the 0–5 cm layer, while for Ca, Mg, B, and Cu, the average difference in this layer was less than 5%. In the 5–30 cm layer, Zn, Fe, and Mn and Cu concentrations tended to be higher in CA, while Ca and B concentrations were similar, and Mg tended to be higher in CP. At the oldest site, Texcoco I, Fe, Zn, and Mn were significantly higher in CA in the 0–5 cm layer, while these differences were not significant at Texcoco II. Concentrations of Cu, Zn, and B were two- to four-times higher than the other sites at Francisco I. Madero, which is irrigated with sewage water, but there were no significant differences between CA and CP (Figure 3 d–f). At Molcaxac, B was significantly higher under CA in the 0–5 cm layer. No B toxicity effects were observed, as maize yields at Francisco I. Madero were among the highest across sites and yields at Molcaxac are below 2 t ha^{-1}, due mainly to terminal drought.

There was no strong overall trend to more stratification in CA, with the exception of nitrate, which was significantly different between the 0–5 cm and 5–30 cm layer under CA at eight sites, but only at three under CP. K and Mn were also significantly higher in the 0–5 cm layer at eight sites under CA and at five (K) and six (Mn) sites under CP. The other nutrients differed between layers at fewer than three sites.

In general, pH was similar under CA and CP, being just 0.1 lower in CA (Figure 4a). Significantly lower pH in CA was observed in the 0–5 cm layer at Indaparapeo and in the 5–30 cm layer at San Miguel Tlacamama and Texcoco II. When exchangeable Al^{3+} and H^{+} were detected, the concentration of these elements was generally lower under CA in the 0–5 cm layer (27 and 31 ppm Al^{3+} and 1.4 and 1.7 ppm H^{+}, respectively) and higher in the 5–30 cm layer (24 and 18 ppm Al^{3+} and 1.1 and 1.0 ppm H^{+}, respectively), although in Indaparapeo Al^{3+} and H^{+} were higher in CA. H^{+} was only significantly lower in CA in the 0–5 cm layer in Metepec and 5–30 cm layer in San Juan Cotzocón, while Al^{3+} was never significantly different in the 0–5 cm layer and only significantly lower in CA in the 5–30 cm layer at San Martin Hidalgo. Boron levels were high at Molcaxac and Francisco I. Madero.

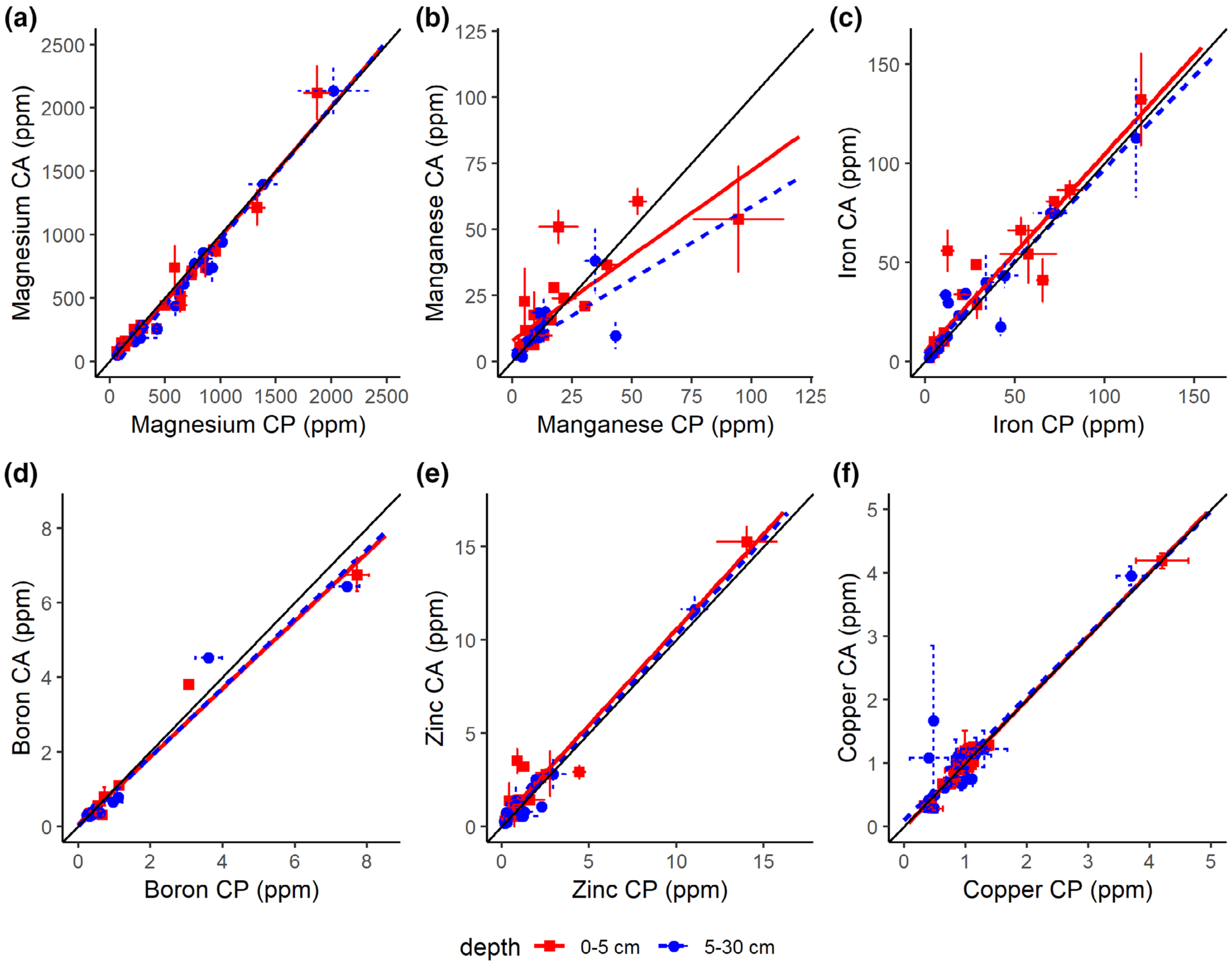

FIGURE 3 Scatter plots of magnesium, manganese, iron, boron, zinc, and copper concentrations in the 0–5 cm (red) and 5–30 cm (blue) layers. Points indicate the sites, with Conventional practices (CP) treatments represented on the x-axis and the corresponding conservation agriculture (CA) treatments represented on the y-axis. Error bars indicate standard error. The black line indicates the 1:1 relationship, points above this line are higher in CA, while points below this line are higher in CP. The regression lines are illustrative of the general deviation from the 1:1 relation and do not indicate a regression model [Colour figure can be viewed at wileyonlinelibrary.com]

Sodium concentrations varied widely across sites, depths, and treatments, from 7 ppm under CA at the 5–30 cm layer at San Juan Cotzocón to 975 ppm at Francisco I. Madero in the 5–30 cm layer under CP (Figure 4d). On average, Na concentrations were lower under CA, specifically 25% lower in the 0–5 cm layer and 6% lower in the 5–30 cm layer. However, within-site variation was large and there

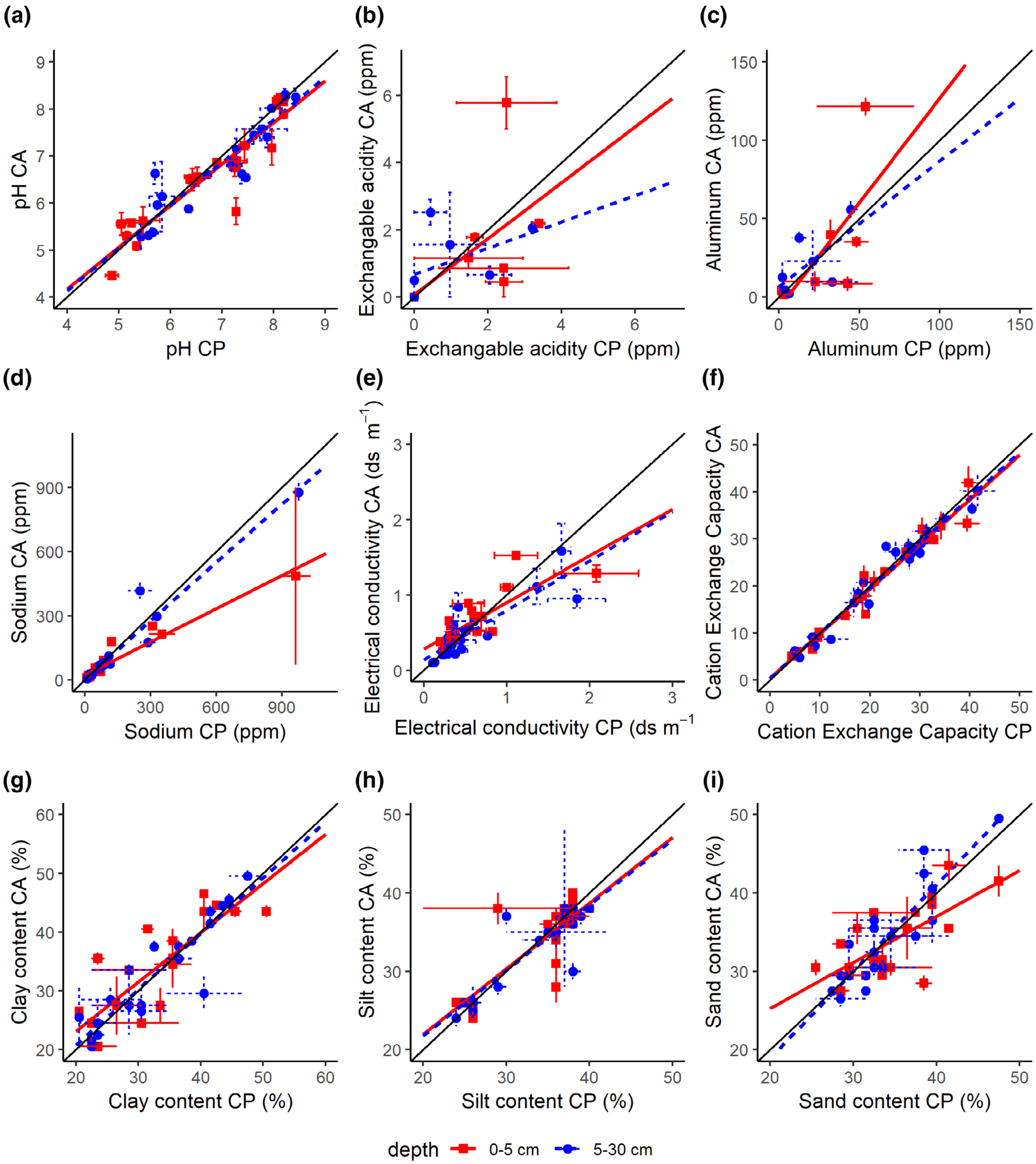

FIGURE 4 Scatter plots of soil health parameters in the 0–5 cm (green) and 5–30 cm (red) layers. Points indicate the sites, with the conventional practices (CP) treatments represented on the x-axis and conservation agriculture (CA) treatments represented on the y-axis. (a) pH, (b) Exchangeable acidity (H^+), (c) Aluminum concentration, (d) Sodium concentration, (e) EC, and (f) Cation exchange capacity. Error bars indicate standard error. The black line indicates the 1:1 relationship, points above this line are higher in CA, while points below this line are higher in CP. The regression lines are illustrative of the general deviation from the 1:1 relation and do not indicate a regression model [Colour figure can be viewed at wileyonlinelibrary.com]

were no significant differences in Na concentrations at any one site. The EC was on average 12% higher under CA in the 0–5 cm layer and 10% lower in the 5–30 cm layer. In the 0–5 cm layer EC was significantly lower under CP at five sites. The exception was Pénjamo, where EC was 40% lower under CA in both layers. Cation exchange capacity did not differ between CA and CP, although it was significantly lower under CA at Apaseo el Alto and Cadereyta in the 0–5 cm layer.

On average in the 0–5 cm layer across sites, clay content was 32.7% under CA, and 31.1% under CP, silt content 33.5% under CA and 34.1% under CP, and sand content was 33.8% under CA and 34.8% under CP. In the 5–30 cm layer, differences were smaller (Figure 4g–i).

3.2 | Physical soil health indicators

Dry sieving MWD was on average 2.31 mm for CA and 2.37 mm for CP, being significantly lower for CA at five of the sites and never significantly higher. Wet sieving MWD was on average 1.44 mm for CA and 0.96 mm for CP, being significantly higher for CA at five sites and never significantly lower. Aggregates were thus on average more stable under CA in the sampled sites. There was generally no difference in aggregate distribution over sites, but CA treatments had significantly higher aggregate stability (Figure 5). Wet sieving MWD was strongly correlated with SOM (r = 0.70, $p < 0.0001$), while dry sieving MWD was not correlated with SOM ($p = 0.09$).

Of the eight sites where direct infiltration was measured, although it was higher under CA at six sites, it was only significantly so at Metepec, which features exceptionally high infiltration rates for all treatments, and Texcoco I, where CA was implemented since 1991. At Apaseo el Alto, Cadereyta, Indaparapeo, Francisco I. Madero, Texcoco I, and San Juan Cotzocón, there were no differences in penetration resistance between CA and CP at any depth. At San Juan del Rio, penetration resistance was significantly lower under CP in the 0–10 cm layer, but was very low, below 0.4 MPa, in both treatments, so there was no indication of compaction. At Metepec, penetration resistance was significantly lower under CP in the 15–30 and 30–45 cm layers but not in the other layers. No compaction was detected at that site, as all measurements were below 1.0 Mpa. At Texcoco II, penetration resistance was significantly higher under CP in the 45–60 cm layer, indicating compaction, with a penetration resistance of 0.8 Mpa under CA versus 2.5 Mpa under CP. Overall, the data of the nine measured sites do not indicate a difference in

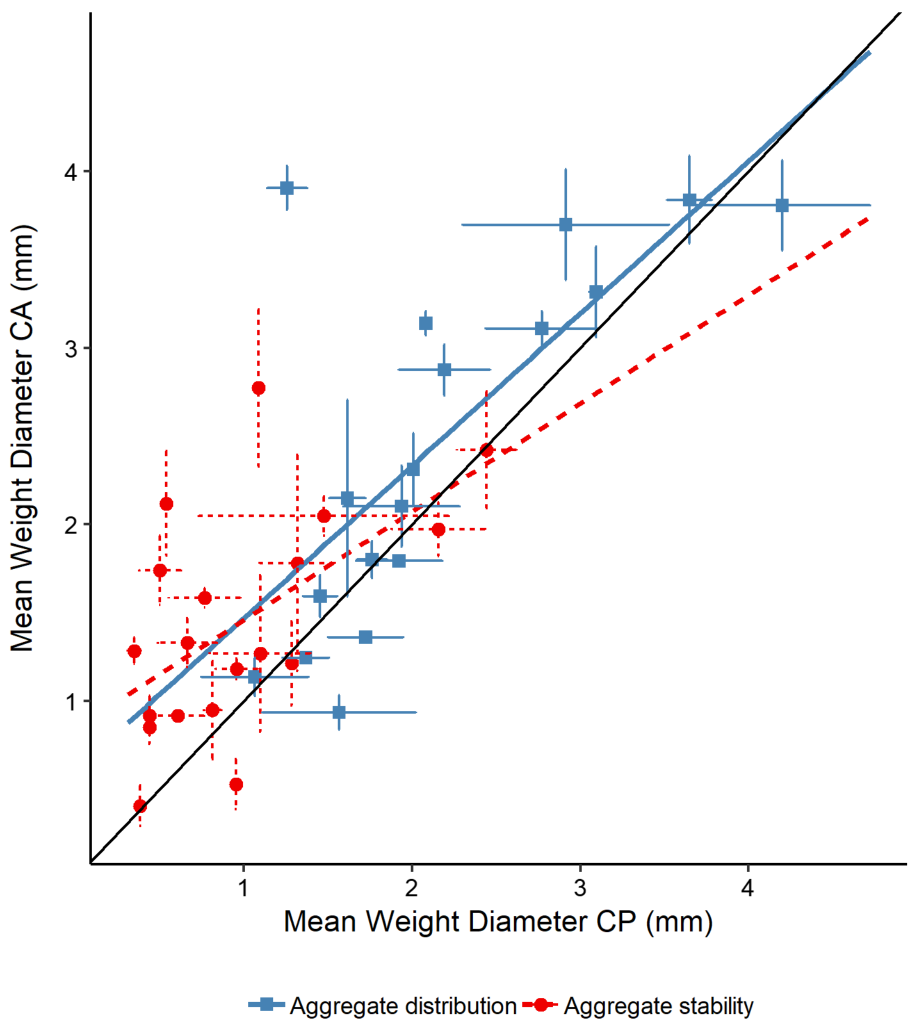

FIGURE 5 Scatter plots of aggregate distribution (blue) and aggregate stability (red) diameter in the 0–5 cm layer under conservation agriculture (CA) and conventional practices (CP). The conventional practices (CP) treatments are represented on the x-axis and conservation agriculture (CA) treatments on the y-axis. Error bars indicate standard error. The black line indicates the 1:1 relationship, points above this line are higher in CA, while points below this line are higher in CP. The regression lines are illustrative of the general deviation from the 1:1 relation and do not indicate a regression model [Colour figure can be viewed at wileyonlinelibrary.com]

compaction between CP and CA, at least close to the sowing line with controlled traffic.

3.3 | Principle component analysis of soil health results

The first and second components of the PCA explained 50% of the variation in the dataset, with each other component explaining less than 10%; therefore, interpretation of the results was limited to the first two components. Since Zn, Cu, Na, and B were strongly correlated with K (R > 0.6, $p < 0.05$), these were not included in the PCA dataset; likewise, H^+ and Al^{3+} were not included as they were strongly correlated with pH. Principal component 1 was highly positively correlated (R > 0.4, $p > 0.05$) with cation exchange capacity, Ca, electrical conductivity, K, Mg, Na, and negatively correlated with Fe and Mn. PC 2 was highly correlated with OM and aggregate stability, while pH, clay content, sand content, and aggregate distribution were highly correlated with both components. Observations for CA and CP did not cluster separately in the biplot of the two most important PCA components; rather the data clustered according to soil texture and soil type (Figure 6) showing that soils were more strongly characterized by soil type and texture than by management, which complicates observing overall trends. The two sites at the same research station, Texcoco I and Texcoco II, clustered together, despite age and differences in production systems. Procrustes analysis showed that the factors differing most between CA and CP in the 0–5 cm layer were S, nitrates, MWD dry, Mn, and MWD wet, indicating these as the most generally contrasting parameters between CA and CP, while other parameters were more influenced by site characteristics than production system (Figure S2).

3.4 | Maize yield

On average, maize yielded 848 kg ha^{-1} more under CA (Figure 7). The difference was largely not significant except at the longest-running sites, Texcoco I, and Soledad the Graciano Sanchez, where yield was significantly higher under CA. At Hopelchén, soil sealing under CA required re-sowing the CA treatment and hence gave lower yields. When Texcoco I, Soledad de Graciano Sanchez, and Hopelchén are excluded from the dataset, the average difference in yield was 879 kg ha^{-1}.

4 | DISCUSSION

CA had beneficial effects on soil health, especially higher SOM and nitrate and S concentrations in the upper soil layer (Figure 2) and a higher aggregate stability (Figure 5). SOM, soil nitrogen, and soil aggregation are strongly linked, and it is to be expected that all three are impacted together, as SOM contains organic nitrogen and soil aggregates physically protect SOM, which binds together the aggregates and increases stability (Hidalgo et al., 2019; Six, Conant, Paul, & Paustian, 2002). Furthermore, several factors lead to higher aggregate stability in CA, including reduced breakdown due to reduced physical disturbance, reduced slaking due to protective residue cover, and increased soil macrofauna and mycorrhizal hyphae (Verhulst et al., 2010). Similarly, in a review of long-term experiments on no-till and conventional tillage in Europe and China, no-till was characterized by higher aggregate stability and SOM, while soil pH did not generally distinguish no-till from conventional till (Bai et al., 2018).

No differences in SOM between CA and CP were detected at sites with lower productivity (sites with an average maize yield <5 t ha^{-1}), but not all sites with higher maize productivity had significant

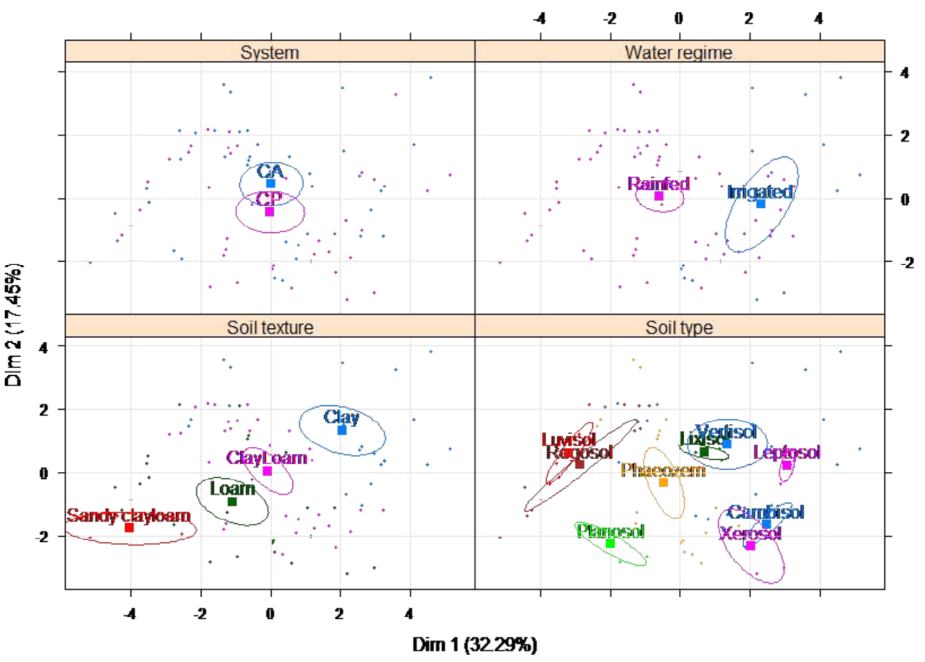

FIGURE 6 PCA analysis clustered according to production system, water regime, soil type, and soil texture. The ellipses indicate the 95% confidence interval of the mean of the observations [Colour figure can be viewed at wileyonlinelibrary.com]

differences in SOM between CA and CP. However, p values were 0.09 and 0.06 for high yielding sites Pénjamo and San Juan del Rio II, respectively, so a longer duration study or a study with more repetitions would probably show an increase in SOM under CA at these sites. Older sites tended to show larger differences in SOM between CA and CP, although Cuautempan (started in 2015) also had significantly higher SOM in CA, there the double cropping under CA and the temperate climate may have sped up SOM accumulation in CA. Although not a time series of measurements at the same locations, the data trend in Figure S1 suggests that the differences in SOM at the older sites are due as much to SOM losses under CP as to SOM increases under CA. Often, CA is described as a possible method to sequester carbon (Powlson et al., 2016), but it actually might be more effective at impeding carbon losses. Similarly, in a 55 year study in Uruguay, SOM decreased by 22% under CP, while it increased by 11% in a crop-pasture rotation (Grahmann, Rubio, Terra, & Quincke, 2020). Other practices may be required to substantially increase SOM under CA, such as more intensive, irrigated cropping, as at Pénjamo, or manure applications as at Molcaxac; both sites had SOM levels over 4%, which is high for Mexican conditions. Sulfur levels were higher under CA in the top layer at several sites, while being higher under CP in the 5–30 cm layer (Figure 2e). Sulfur often comes from atmospheric deposition and can be released by decomposing residues, which may explain an increase in the top layer under CA and a mixing in the deeper layer under CP. However, the S cycle is very dynamic, with rapid mineralization and leaching and accurate testing is difficult (Jamal, Moon, & Abdin, 2010); further study may be needed to determine whether soil S content is indeed different in CA.

Nitrate concentrations were higher under CA at 0–5 cm (Figure 2b), as were those of nutrients such as P, K, Fe, Mn, and Zn on average, though not at all sites (Figures 2 and 3). This may be a result from residue retention under CA versus removal or incorporation under CP in many sites. The higher EC under CA (Figure 4b) was probably caused by this accumulation of nutrients in the 0–5 cm layer. Higher concentrations of nutrients such as N (Grahmann et al., 2020), P (Fonteyne et al., 2019), and K (Singh et al., 2018) have been reported in other studies, but it is still unclear how residue retention impacts soil nutrient cycles and fertilization requirements. A review in Africa showed CA required supplemental N fertilization to correct for N immobilization by residues (Thierfelder et al., 2018), although other studies have shown that subsurface fertilizer application can reduce N immobilization under CA (Grahmann, Verhulst, Buerkert, Ortiz-Monasterio, & Govaerts, 2013). Here, differences seemed to be more common in the Phaeozems and Luvisols than in soils with high clay content, as no macronutrient differences were observed at Vertisol sites (although these too are more heavily fertilized in view of their higher expected yields).

At some sites, the clay fraction was higher under CA in the 0–5 cm layer, while in the 5–30 cm profile, no differences in clay content were observed (Figure 4g), possibly a result of greater erosion under CP whereby the lighter fraction gets lost first (Lichter et al., 2008). Wind erosion in cultivated fields can lead to an increase in sand content, although whether clay or silt removal is higher depends on the soil texture (Colazo & Buschiazzo, 2015; Lyles & Tatarko, 1986). The sites with the largest changes in clay content all have long periods in winter when the cultivated soil is open to wind erosion. Soil cover and improved infiltration reduce erosion in CA. Infiltration rates have often been found to be higher under CA (Govaerts et al., 2007; Thierfelder & Wall, 2009), but our study showed differences between CA and CP only at two sites.

Maize yields were about 0.85 t ha^{-1} higher under CA (Figure 7), indicating that when all three CA components were combined and adapted to the local conditions, CA yielded more than CP. In Hopelchén, lower yields under CA were caused by surface sealing, which could be resolved by better adapting the sowing method. The increased yields may be a result of improved soil health, as apart from the treatment factors, the other management was kept the same. At Texcoco I, soil health has been studied extensively and, compared to conventional tillage, soils under CA have higher infiltration rates, maintained higher moisture contents throughout the growing season, and gave higher yields (Verhulst et al., 2011). At Soledad de Graciano Sánchez, the infiltration rate was considerably higher under CA, improving irrigation efficiency and raising maize yields (Fonteyne et al., 2019). Measurements were made on top of permanent raised beds or close to the sowing line in flat planting, to foster comparability between samples and because this is the most relevant zone for plant growth. It is likely that SOM and nutrients are not distributed uniformly in the field under CA, given that in permanent beds, for instance, furrows are reshaped but bed tops are moved only by sowing and fertilization and, under zero tillage, plant rows are in the same place every year, at least in our experimental settings. Therefore, these results should not necessarily be extrapolated to field level but should be interpreted as an increase in soil health under CA where

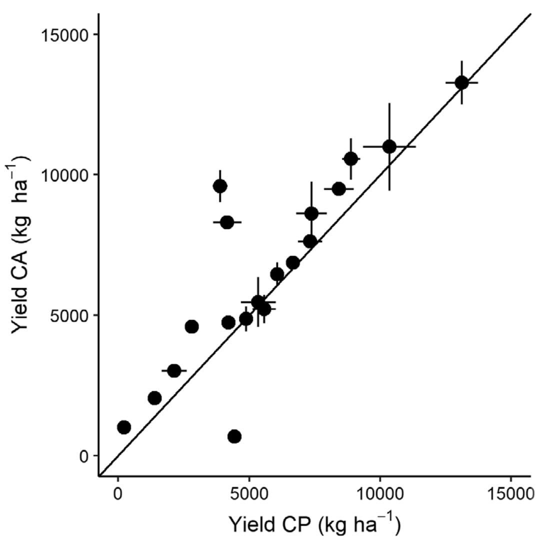

FIGURE 7 Yield under CA versus yield under CP, 2018. Error bars indicate standard error. The black line indicates the 1:1 relationship. Yield is for maize grain at 14% moisture content, except for CA in San Miguel Tlacamama, where yield is a mixture of maize and beans (*Vigna unguiculata* (L.) Walp)

the plants are growing. Differences in the measured parameters tended to be larger in the longest running sites and several of our sites have been in place less than 5 years; therefore, our results should be interpreted as general results of CA implementation, not the maximum benefits that CA can generate in terms of soil health. For this, longer-term studies are needed.

Most soil health parameters were determined more by local soil conditions than by management. CA effects on soil health were site-specific, while PCA does distinguish CA and CP at individual sites (Govaerts, Sayre, Lichter, Dendooven, & Deckers, 2007; Lichter et al., 2008), and soil properties clustered by soil type rather than by management, across sites (Figure 6). Due to budget constraints, this study focused on only 20 of the 60 research platforms currently in CIMMYT's network. Since the specific effects of CA on soil health, apart from SOM, aggregate stability, and nitrates, cannot be broadly extrapolated from results at specific sites, agronomic research in each agro-ecology under farmers' conditions is still needed, to identify locally adapted practices that improve both yield and soil health (Cassman & Grassini, 2020; Erenstein, Sayre, Wall, Dixon, & Hellin, 2008) and to avoid generalization based on a limited number of trials with successful results.

5 | CONCLUSIONS

CA increased SOM, nitrate, and sulfur concentrations and aggregate stability in the topsoil layer compared to CPs. Other soil health parameters differed among sites, indicating a strong effect of local conditions on the impacts of CA vis a vis soil health. No adverse effects of CA, such as acidification or compaction, were observed and maize under CA tended to yield more. The diverse effects of CA on soil health make it necessary to evaluate it in adaptive trials in each agro-ecology system and thereby adapt it to the local conditions.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data are openly available in Dataverse at https://data.cimmyt.org/dataset.xhtml?persistentId=hdl:11529/10548506 (Verhulst & Fonteyne, 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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