Effects of Conservation Tillage on Water Supply and Rainfed Maize Production in Semiarid Zones of West-Central Mexico

Eric Scopel, François Tardieu, Gregory Edmeades, and Michel Sebillotte

Introduction

Tropical semi-arid zones are usually characterized by large variation in physical conditions, both over time (variation in weather among years) and locations (climatic and edaphic conditions). The success of techniques to improve crop production and yield stability in these zones depends on the good management of the production factors which are most limiting to crop yields over time. The level of those factors is related to interactions of physical conditions with crop management practices (Sebillotte, 1989). In tropical environments, when rainfall during the main cropping season is limited and/or irregularly distributed (generally below 500 mm annually), rainfed maize production is strongly determined by crop water use (Claassen and Shaw 1970; Muchow and Sinclair 1991).

Soil tillage can affect water availability to plants (Al-Darby et al. 1987; Chopart 1990; Gajri et al. 1992; Hamblin 1984; Lal et al. 1978; Ogunremi et al. 1986; Ojeniyi 1986), essentially via two factors: 1) soil water capture and 2) root uptake capacity. Soil tillage and mulching can change the capacity of the soil surface to intercept rainfall by affecting the hydraulic conductivity of the topsoil, soil roughness, and soil surface porosity. Mulching is also a well-known technique for conserving water by reducing direct evaporation (Unger and Parcker 1976; Steiner 1989) and increasing water storage (Duley and Kelly 1939; Osuji 1984; Steiner 1994).

The ability of root systems to take up water can vary appreciably with soil structure, essentially through changes in root length density and root spatial arrangement (Tardieu 1988b; Tardieu et al. 1992a). Zero-till systems can reduce rooting depth (Chopart and Nicou 1976; Unger and Mc Calla 1980). Conservation tillage (CT; defined here as zero tillage with a crop residue mulch cover) shows considerable potential for stabilizing production in semiarid zones, but can have contrasting consequences on water conservation and yield (Lal et al. 1978; Osuji 1984; for positive effects. Chopart and Kone 1985; Wilhelm et al. 1987; for negative effects). This variability could be due to different balances across fields and years between positive effects on water storage and negative effects on water uptake by plants. We have tried to analyze both effects separately in our study comparing tillage treatments.

On the other hand, to really understand the effects of increased water availability on maize grain yields, it is important to consider both the quantity and timing of water availability, since maize varies considerably in its susceptibility to water deficits throughout its life cycle (Claasen and Shaw 1970; Grant et al. 1989; Bolaños and Edmeades 1993). Monitoring crop water use by estimating actual evapotranspiration (ETa) provides information on a key component of the crop water balance and hence on crop-available water. The magnitude of ETa in relation to potential evapotranspiration also indicates the extent to which the crop's water needs are being satisfied and, hence, the level of drought stress (Bennett et al. 1986).

When rainfall during the crop season exceeds 500 mm and is evenly distributed over time, crop production depends on a range of other factors, especially nutrient availability and weed control (Affholder et al. 2001; Wey et al. 1998). Where water is essentially non-limiting, CT might be less attractive to maize farmers in the short term, although few published studies address this issue (Scopel and Chavez Guerra 1999).

The objective of the present study was to determine the potential of CT for improving maize productivity under a range of soil and rainfall conditions in a semiarid zone of Mexico. For this, we tried to evaluate the respective consequences of tillage practices on the crop's ability to take up water (analyzed during dry periods of the cycle) and on soil storage of rainfall water (analyzed during rainy periods of the cycle). Finally, we analyzed the consequences on ETa, on crop physiology, and on grain yield. To reflect closely farmers' circumstances, the study was conducted under the cropping systems typical of small-scale farmers in the target zone. Since part of the maize crop residue is grazed by cattle during the dry season, a realistic but low level of mulch (around 2 t/ha dry matter) was used in the CT treatments.

Materials and Methods

Sites and Experimental Design

The experiments took place over 1990-91 at four locations in western Mexico of distinct soil and climatic conditions (Table 1). The sites represent the target area's two major soil types (black vertisol and brown volcanic loam) and moisture environments (dry vs. wet).

The experimental design used at each site was a split plot (subplot area: 150 m^2) with two replications in which the main plots comprised soils with the residual effects of a subsoiling carried out in 1990 to a depth of 0.4 m with a twin tine (0.80 m width) subsoiler. Four soil tillage treatments were used in each subplot:

- Zero tillage with an evenly applied mulch of 0.2 kg/m^2 dry matter (termed "CT").
- Two light diskings (7-10 cm depth) with a tandem disk harrow, 2 m width, with no mechanical control of weeds (termed "DO"), in 1990. In 1991 this treatment was changed to zero tillage without residue (termed "NT").
- Two light diskings (7-10 cm depth) with a tandem disk harrow, 2 m width, followed by mechanical control of weeds with animal traction (termed "DM").
- Disk plowing (15-20 cm depth) followed by disk harrowing and mechanical control of weeds (termed "PM").

Treatment DM represented the traditional system of land preparation in this area; PM is also used, but much less frequently. All tilled treatments were established under dry conditions in May to avoid soil compaction.

A local, open-pollinated maize variety (Criollo Amarillo) known to be well-adapted to the dry conditions of the zone was sown. Seeds were coated with the insecticide Carbofuran at 50 g/kg product. Fertilizer was applied at 140 kg/ha N split among thr ee applications (20 kg N in the sowing row, 60 kg N banded 21 d after sowing, and 60 kg N banded 45 d after sowing) and 60 kg/ha P_2O_5 in the sowing row. Weeds were controlled with a pre-emergent herbicide (paraquat + atrazine + metolachlor mixture) applied at recommended rates, by mechanical control 21 to 28 d after sowing in treatments DM and PM, and by manual control when necessary after that time. Total daily rainfall was collected in graduated plastic rain gauges installed at each site. Soil bulk density was measured on non-perturbed soil volumes, sampled with cylinders (75 cm^3) at 0.05, 0.15, 0.25, 0.50 and 0.70 m depths in each plot at maize silking. Penetrometer resistance was measured with an electronic Penetrometer (REMIK, Australia) at the same stage in 1991 at 15 mm intervals over a 0.45 m depth. Within each plot, three series of measurements were carried out in the row and three in the inter-row. The average of the six readings was used in subsequent analyses.

Soil water content was measure only at dry sites on a volumetric basis every fourth day during dry and rainy periods (Fig. 1). Measurements were carried out in the 0.2-1.0 m part of the profile in each plot using a neutron probe (TROXLER 3300) every 0.2 m of a 5.0 cm diameter aluminum access tube. The neutron probe was calibrated in situ by simultaneously measuring soil water content (gravimetric measurement, 100 cm^3 samples) and neutron probe count every 0.2 m of each tube, at the beginning and the end of each crop cycle. In 1990, two access tubes were placed in each plot of treatments CT and DM (8 tubes per treatment). In 1991, three access tubes were placed in each plot of treatments NT, CT, and DM (6 tubes per treatment). Soil moisture contents were measured gravimetrically at two points around each access tube in the upper 0-20 cm of the profile. Soil samples (100 g wet weight) were collected from two sites adjacent to the neutron probe access tubes, dried in a forced air oven at 105 °C to constant weight, and re-weighed. Using estimates of bulk density taken from the same areas in each plot, soil moisture measurements were converted from a dry weight basis to a volumetric basis. Non-available water was determined for each 0.2 m soil layer measuring soil water content at a water potential of -1.5 MPa (pressure cook technique). In addition, the depth of the wetting front at the onset of rains was determined in 1991 by digging with an auger and measuring the depth of dry soil in each plot. Sampling was carried out three times at site 1 and once at site 2 between the onset of the rains and 3 weeks after planting.

The root system was characterized two weeks after silking, when maize roots are longest (Mengel and Barber 1974; Tardieu and Manichon 1987). An area free of weeds and with regular plant spacing was selected in each field. A 0.8 m trench was dug, centered on and perpendicular to a plant row, and a smooth vertical face (0.8 x 1.2 m) was prepared. Roots were made visible by removing a few millimeters of the surrounding soil using a knife. A 20 mm grid mesh was placed on the face, and the presence or absence of root contacts was marked in each 20 x 20 mm square (a root contact is the intersection of any root with the observed plane). The root contact frequency was calculated in each 0.02 m layer as the proportion of squares with at least one root contact (Tardieu 1988a).

Actual evapotranspiration (ETa) was estimated during dry periods by differences of total soil moisture between two successive observations, eventually corrected for the amount of rain (few events of less than 5 mm, so without runoff).

Table 1. Sites of experiments to determine the potential of conservation tillage for improving maize productivity in the municipality of Venustiano Carranza,* Jalisco state, western Mexico, 1990-91.

No.	Site	Altitude (meters above sea level)	Water availability	Soil type	Soil pH
1	La Tinaja	1,150	Dry	Cambisol (12% clay, 25% loam, 63% sand).	6.0
2	Cuatro Caminos (1990) Campo Experimental (1991)	1,000	Dry	Vertisol (35 to 45% clay, 25% loam, 30-40% sand).	7.0-8.5
3	San Isidro	1,350	Wetter	Cambisol (12% clay, 25% loam, 63% sand).	6.0
4	Alista	1,350	Wetter	Vertisol (35 to 45% clay, 25% loam, 30-40% sand).	7.0-8.5

* A semiarid zone located at 19.5 ° N, 104 ° W.

Leaf water potential was measured using a pressure bomb (Soil Moisture Corporation, California) on 8 to 10 leaves (one leaf at ear level per plant) of each plot. We did this between 10 and 12h (solar time) on one occasion after several dry days (06 August 1990 and 24 August 1991 at La Tinaja; 16 August 1990 at Cuatro Caminos; 20 August 1991 at Campo Experimental). Stomatal conductance and leaf temperature were measured using a previously calibrated steady state porometer (LICOR LI-1600, Lincoln, NE) on 15 fully exposed and fully expanded upper leaves in each plot. We made the observation at 12h (solar time) on one or two occasions corresponding with the long dry spells and the appearance of midday leaf rolling (06 August 1990 and 18, 24 August 1991 at La Tinaja; 24 August at Cuatro Caminos; 14, 20 August 1991 at Campo Experimental).

When tassels became visible on about half the plants, observations were made every other day on each plant of the two central rows of each plot to determine the number of plants having visible anthers and silks. The number of days from sowing until 50% of the plants displayed anthers (AD) was recorded for each plot and the same for silking (SD). The anthesis-silking interval (ASI) was calculated as SD-AD.

For dry weight at flowering, we used an indirect indicator (j(h) = plant height X (stalk diameter)+) to avoid destroying too many plants. A good linear correlation between j(h) and dry matter has been obtained (r+ = 0.81) on a sample of 60 Criollo Amarillo plants for which total height, stalk diameter at second node, and total dry matter had been measured at anthesis. Then, in each plot, only total height and diameter of the stalk were measured on 20 plants when crop had reached 50% anthesis, to estimate dry matter.

For grain yield and its components we marked off a bordered area of 35 m^2 in the center of each plot when all plants had reached maturity, and counted

Table 2. Rainfall characteristics for each experimental location in 1990 and 1991, Jalisco, Mexico.

Location	Soil type	Total rainfall (mm)	Number of events	Dry periods	Crop development stage
Dry zone 1990					
La Tinaja	Brown soil	385	45	* 07/25-08/10 (16 days)	8 leaves
				* 08/17-09/04 (18 days)	Flowering
				* 09/19-10/04 (15 days)	Post-flowering
4 caminos	Black soil	467	33	* 08/02-08/23 (21 days)	Pre-flowering
				* 08/25-09/07 (14 days)	Flowering
Dry zone 1991					
La Tinaja	Brown soil	395	45	* 08/12-08/29 (16 days)	Pre-flowering
				* 09/08-09/20 (13 days)	Post-flowering
C. Experimental	Black soil	514	29	* 08/08-08/20 (13 days)	Pre-flowering
				* 08/31-09/15 (16 days)	Post-flowering
Humid zone 1990					
San Isidro	Brown soil	693	71		
Alista	Black soil	648	52		
Humid zone 1991					
San Isidro	Brown soil	520	72		
Alista	Black soil	564	52		

the number of plants. Plants whose stem elevation was less than 45° were considered lodged, and lodging counts were recorded. Plants in the marked area were hand-harvested, ears counted, and percentage rotted grain noted. Ears were weighed in the field, and a sample of 15 ears was taken for lab calculation of number of kernels per ear, kernels weight, humidity of the grains at harvest, and the shelling percentage. Grain yields and grains weight have been calculated at a grain moisture content of 0.15 g water per g.

Statistical Analyses

An ANOVA was first conducted at each site. We did no combined analyses across sites or years because of the change of treatments between years and because of the significant interaction between sites and treatments. Yield data from all environments and years were subjected to a principal components analysis (PCA, multivariate analysis) in which yield components and plant characteristics were treated as independent variables and yield the dependent variable to be explained, to analyze which yield component and what factors most influenced yields variability in this network of trials.

Results and Discussion

Rainfall at Each Site

In both seasons, rainfall limited crop production at both dry sites. Total rainfall during the crop cycle at these sites ranged from 385 mm to 514 mm distributed among 29 to 45 events, and with marked dry periods of 12 to 18 days that sometimes coincided with flowering (Table 2, Fig. 1). In the upper and wetter zone, rainfall was generally satisfactory, ranging from 520 mm to 693 mm distributed among 52 to 72 events and with no major dry spells. In general, the 1991 crop season was drier than that of 1990, so the differences between the wet and dry zones were less pronounced in 1991. The normal variation in climatic conditions in this zone were generally well represented in the study environments. Plant growth was generally better than that in farmers' fields surrounding each site. Dry matter at flowering was always more than 0.1 kg per plant (4.3 t/ha) even at La Tinaja, where a dry period at the 8 visible leaf stage caused extensive leaf rolling in the middle of the day. This level of production is similar to that recorded in tropical maize in a similar environment under moderate drought stress by Bolaños and Edmeades (1993).

Yield and Yield Components

Yield varied from 0.06 to 6.1 t/ha, demonstrating the variability of cropping conditions among environments and treatments in this network. Axes 1 and 2 of the principal component analysis of yield by its yield components explained 73.9% of the total variability in grain yield. Principal

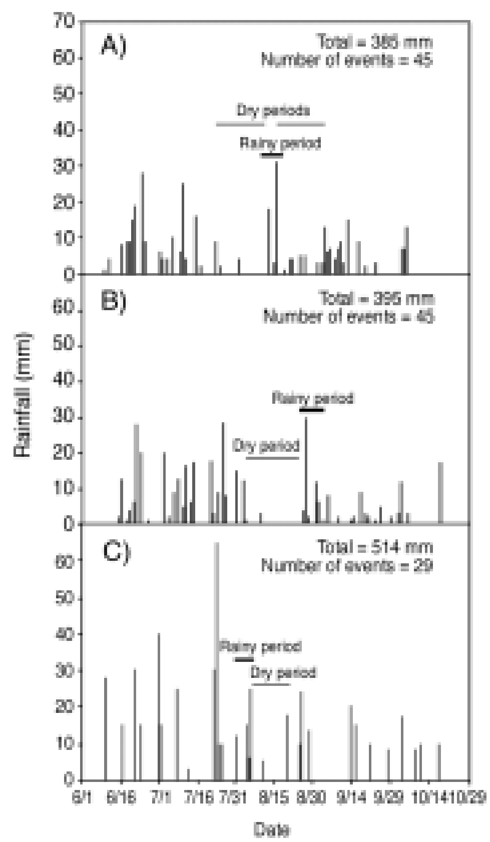
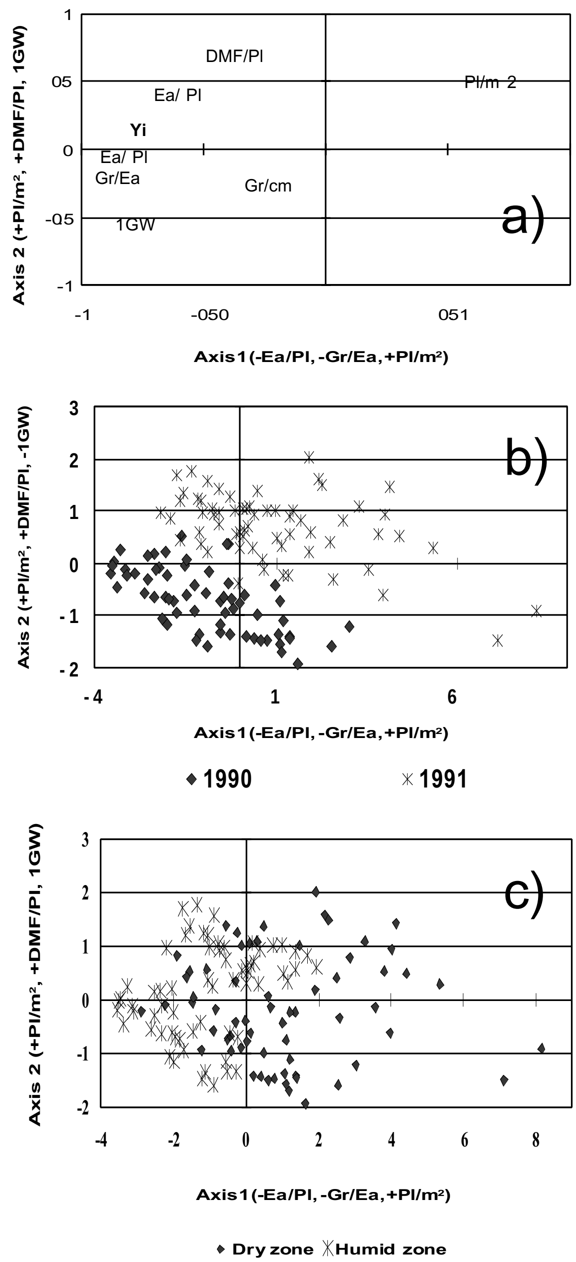


Fig. 1. Distribution of rainfall during the three growing periods, and positions of studied dry and rainy periods. A: Site 1, 1990; B: Site 1, 1991; C: Site 2, 1991.



Yi = Grain yield (additional variable)
PL/M2 = Plants per m2
EA/PL = Ears per plant
GR/EA = Grains per ear
1GW = Weight of 1 grain
EAL = Ear length
GR/CM = Grains per cm of ear length
DMF/PL = Dry matter per plant at flowering

Fig. 2. Principal components analysis of grain yield by yield components, ear morphology and biomass at flowering in the first plan (axes 1-2) projection, for all the treatments of four maize trials grown in 1990-91 in farmers' fields, Jalisco, Mexico: a) correlation between variables; b) position of treatments per year, c) position of treatments per moisture zone.

Component 1 (PC1) was defined mainly by the number of grains per plant. Principal Component 2 (PC2) was related mainly to number of plants per unit area, dry matter per plant at flowering, and to a minor extent weight per kernel. Variation in grain yield was explained mainly by PC 1 (79.3%) and showed much less dependence on PC 2 (20.7%) (Fig. 2a).

Yield was not correlated with plant stand, which varied from 3.5 to 6.2 plants/m^2 over the sites (Fig. 2a). But grain yield was strongly correlated with number of grains per plant and especially with the number of ears per plant (r+ = 0.84**, 127 df), showing the importance of growing conditions during the critical stage of grain number determination. These relationships have also been reported in other studies (Bolaños and Edmeades 1993; 1996). Variation in yield was only weakly associated with variation in weight per kernel. It must be noted that potential yields on the order of 6.0 t/ha (maximum observed with this variety) can be attained with an average weight per grain of 300 mg. In 40% of the plots average weight per grain was less than 300 mg, and each of these was located in the dry zone where several dry spells occurred after flowering.

There were clear differences between the two years that were reflected in the principal components analysis (Fig. 2b). Treatments in 1990 separated from those in 1991 principally for PC2. Plant stand was generally lower in 1990, when heavy rains early in the cycle caused soil capping and water logging. Grain yield and its components affecting number of grains were more variable in 1991, and weight per grain was lower on average in 1991. Similarly, principal components analysis also successfully separated treatments from wet and dry sites (Fig. 2c). Average yields were lower in the dry zone (3.5 vs. 4.0 t/ha in 1990, and 2.7 vs. 4.4 t/ha in 1991), but the variation in yield was larger in the dry sites, confirming the importance of crop water supply, directly dependant on soil preparation treatments, as a major determinant of productivity in this study.

Effect of Tillage Treatments on Maize Production

Tillage treatments resulted in yield responses that depended on the zone and the rainfall pattern (Table 3). In the dry zone, treatments had a large effect and CT always gave the highest yields in both years and on both soil types. Treatments PM and DM gave intermediate results, PM being apparently more effective on the brown soils. DO (and SO in the second year) consistently and sometimes significantly produced the lowest yields on both soils. Differences in grain yield were also reflected in differences in yield components, but especially in number of grains per plant and sometimes in weight per grain, where a dry period occurred after flowering. At the wetter sites the PM treatment produced the largest yields in both soil types, even though treatment differences were not as large and not always significant. Under more favorable rainfall conditions, CT gave yields similar to those of the NT-DO and DM treatments (Table 2). The large differences in grain yield observed among treatments in the drier zone have to be compared with differences in rainfall valorization through soil water capture and crop water uptake.

Soil Water Capture Capacity

The moisture front at the beginning of the crop cycle (Table 4) was 25% to 50% deeper in treatment CT at both sites and for each date, compared to the other three treatments. No significant differences were observed between treatments DM, PM and NT. Changes with time of profiles of soil water content during a rainy period (Fig. 3) at site 1 (La Tinaja) confirm that more water was stored in treatment CT, where an increase in water content was observed down to 0.8 m vs. 0.4 m in treatments NT and DM. Cumulated water storage during three rainy periods for sites 1 (La Tinaja in 1990 and 1991) and 2 (Campo Experimental in 1991) was always larger in treatment CT than in the other two treatments, reaching 91% of rainfall at site 1 1991 and 44 and 74% in the other two periods), whereas it was less than half of rainfall in the other treatments (Table 5). This suggests that appreciable runoff occurred in all treatments, but less in CT, thereby increasing water storage in this treatment. This effect on water storage largely explains why there was always more available water in the soil at both sites over the whole cycle under CT (Table 4), and more significantly after the rainy period. DM represents an intermediate situation between CT and NT.

Differences in runoff vs. rainfall storage during rainy periods are attributable to differences in soil surface roughness (Casenave and Valentin 1991). In treatment NT, a superficial layer of free dust appeared by the end of the dry season; this

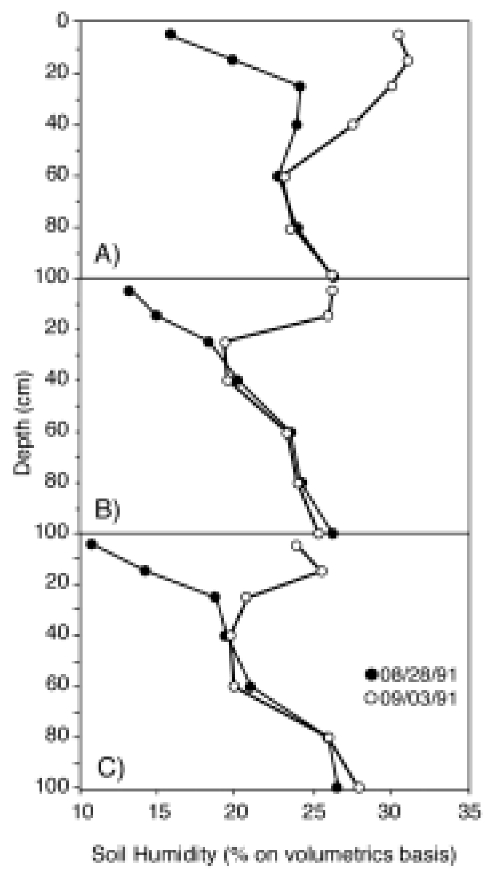


Fig. 3. Profiles of soil water content at the beginning (●) and end of a rainy period (○) from 28 August to 3 September 1991. A: CT, conservation tillage with 0.2 kg m⁻² dry matter mulch; B: NT, zero tillage; C: DM, diskings at 7-10 cm depth.

Table 3. Maize yields and yield components for each experimental location, 1990 and 1991, Jalisco, Mexico.

Location		Tillage treatment[1] CT	NT	DO	DM	PM	SD[2]
Dry zone 1990							
La Tinaja							
(Brown soil)	Grain yield (t/ha)	3.28 b		2.14 a	2.42 a	2.64 a	*
	Ears/plant	0.59 b		0.47 a	0.50 a	0.50 a	*
	Kernels/ear	378		342	356	346	NS
	1,000-kernel weight (g)	319 b		266 a	300 ab	311 ab	*
Cuatro Caminos							
(Black soil)	Grain yield (t/ha)	5.08 b		4.53 ab	4.07 ab	4.86 a	*
	Ears/plant	0.76 b		0.71 ab	0.66 ab	0.60 a	*
	Kernels/ear	415		400	388	389	NS
	1,000-kernel weight (g)	373 b		365 ab	362 ab	342 a	**
Dry zone 1991							
La Tinaja							
(Brown soil)	Grain yield (t/ha)	3.06 c	0.45 a		1.84 b	1.93 b	**
	Ears/plant	0.58 c	0.13 a		0.41 b	0.39 b	**
	Kernels/ear	331 c	209 a		266 b	280 b	**
	1,000-kernel weight (g)	282	253		272	275	NS
C. Experimental							
(Black soil)	Grain yield (t/ha)	4.97 b	2.59 a		2.91 a	3.45 a	**
	Ears/plant	0.79 b	0.55 a		0.61 a	0.66 a	**
	Kernels/ear	436 c	322 a		360 b	380 b	**
	1,000-kernel weight (g)	320	285		299	287	NS
Humid zone 1990							
San Isidro							
(Brown soil)	Grain yield (t/ha)	3.18 a		2.94 a	3.10 a	3.69 b	*
	Ears/plant	0.56		0.56	0.56	0.57	NS
	Kernels/ear	398 a		412 a	398 a	472 b	*
	1,000-kernel weight (g)	350		353	326	346	NS
Alista							
(Black soil)	Grain yield (t/ha)	4.53 a		4.63 a	4.58 a	5.42 b	*
	Ears/plant	0.74 a		0.75 a	0.73 a	0.86 b	*
	Kernels/ear	428 a		466 ab	468 ab	49 b	*
	1,000-kernel weight (g)	345		367	348	374	NS
Humid zone 1991							
San Isidro							
(Brown soil)	Grain yield (t/ha)	4.17	4.00		4.16	4.73	NS
	Ears/plant	0.71	0.76		0.75	0.82	NS
	Kernels/ear	399	379		392	444	NS
	1,000-kernel weight (g)	279	286		277	283	NS
Alista							
(Black soil)	Grain yield (t/ha)	4.12 a	3.63 a		4.28 a	5.86 b	**
	Ears/plant	0.65	0.69		0.66	0.78	NS
	Kernels/ear	344	348		352	396	NS
	1,000-kernel weight (g)	309	299		303	324	NS

1. CT = Conservation tillage; NT = no tillage; DO = light disking + without mechanical weed control; DM = idem DO with mechanical weed control; PM = Disk plowing.

2. ** Significant differences at P=00.1; * significant differences at P=0.05; NS = non-significant differences; treatments with the same letter did not differ according to the Tukey test.

was rapidly transformed into a continuous crust by the first rains. The same process was observed in treatments DM and PM, where free dust was caused by disk action, reducing saturated hydraulic conductivity, as described by Hillel and Gardner (1970). Under CT residue covered 30% of the surface area at a mulching rate of 0.2 kg/m^2, increasing roughness and buffering the kinetic energy of rain water to reduce erosion and crusting. The effect of mulch on direct evaporation from the soil was not assessed in this study. Because of the major effect of mulch on rain water storage and because of the low rate of coverage (around 30% on average), we hypothesized that the effect on evaporation was not significant, given the high soil depletion rate for CT with mulch during dry periods. The more intense root colonization under CT in the 0-10 cm layer probably accelerated uptake by plants, thus reducing direct evaporation.

Table 4. Moisture front depth in the soil profile at the beginning of the cycle for four tillage treatments at two sites, Jalisco, Mexico, 1991.

Site and date	Crop development stage	Accumulated rain from beginning of cycle	Moisture front depth (cm) CT[1]	NT	DM	PM	SD[2]
Site 1(06/23)	Before planting	53mm	24.5b	12.3a	10.8a	12.3a	**
Site 1(07/02)	Planting	74mm	31.0b	15.3a	18.5a	18.5a	**
Site 1(07/22)	20 days after planting	163mm	62.3b	42.3a	48.0a	43.0a	**
Site 2(06/20)	Before planting	43mm	19.5b	12.8a	11.8a	11.0a	**

1. CT = Conservation tillage; NT = no tillage; DM = light disking + mechanical weed control; PM = Disk plowing.
2. ** Significant differences at P = 0.01; treatments with same letter did not differ significantly according to the Tukey test.

Table 5. Available water at the beginning and at the end of a rainy period and additional water stored in the profile during this period for different tillage treatments at two sites in Jalisco, Mexico, during 1990-1991.

Site (date)		Available water in 100 cm soil profile (mm) CT[1]	NT	DM	SD[2]
Site 1 (08/10/90)		84		69	NS
Site 1 (08/17/90)		107		80	*
Site 1 (08/28/91)		54	29	44	NS
Site 1 (09/03/91)		93b	51a	69a	*
Site 2 (08/05/91)		139b	56a	85a	*
Site 2 (08/08/91)		142b	65a	96a	*
Site (period)	**Accumulated rain during the period**	**Additional water stored in the profile (mm) during the period: CT**	**NT**	**DM**	
Site 1 (from 08/10/90 to 08/17/90)	52mm	23		11	*
Site 1 (from 08/28/91 to 09/03/91)	43mm	39a	22b	25b	*
Site 2 (from 08/05/91 to 08/08/91)	31mm	23a	9b	11b	*

1. CT = Conservation tillage; NT = no tillage; DM = light disking + mechanical weed control; PM = Disk plowing.
2. * Significant differences at P=0.05; NS = Non-significant differences; treatments with same letter did not differ significantly according to the Tukey test.

Root System Differentiation

Root elongation is strongly related to soil physical conditions (Tardieu 1988a). Bulk density differed among locations (lower at Campo Experimental than at La Tinaja) and among experimental plots in each location (Fig. 4). It was reduced in all experiments by the loosening action of disks in the 0-0.1 m and 0-0.2 m soil layers in treatments DM and PM respectively, with a greater effect at site 1 than 2. In contrast, it was highest in treatments CT and NT in the same layers under undisturbed conditions. Penetrometer resistance could not easily be compared between locations, since a 25 mm rain occurred the day before measurements at site 2 (Fig. 5). Differences in resistance among treatments were therefore reduced in the upper part of the profile (0-25 cm) at this location. Nevertheless, treatment NT was associated at both sites with higher penetrometer resistance over the whole profile, whereas treatment PM resulted in a lower resistance in the 0-0.2 m layer loosened by tillage. Treatments CT and DM gave intermediate values in the upper part of the profile (0-0.2 m) becoming lower for CT treatment between 0.2 and 0.4 m. Increased penetrometer resistance in treatment NT and decreased resistance in treatment CT were linked to differences in soil water content (Fig. 3), as no difference in bulk density was detected between the two.

Profiles of root contact frequency (Fig. 6) had a common pattern across treatments and locations, with highest frequencies in the uppermost 0.0-0.1 m layer and appreciable colonization down to the 0.8 m depth. In all cases, more than 80% of root contacts were located in the uppermost 0.4 m of the profile. In 1990 (site 1), roots were clumped in the 0.0-0.1 m layer and frequency was low in subsequent layers regardless of the treatment. This pattern was conserved in treatment CT of the same site in 1991, although with slightly denser root contact frequency in the 0.1-0.8 m layer. In

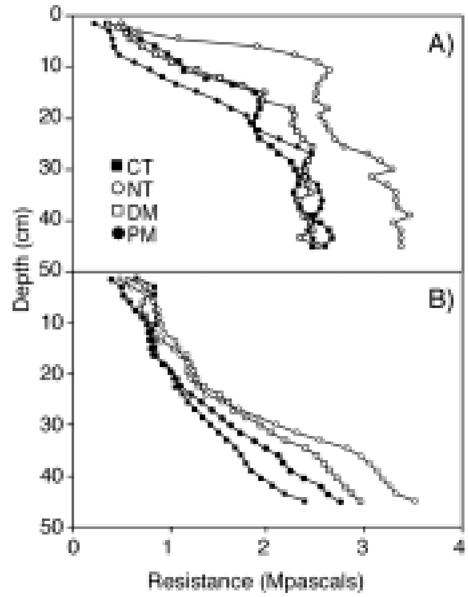


Fig. 5. Profiles of penetrometer resistance with four tillage systems. A: Site 1, 1991; B: Site 2, 1991. Symbols as in fig. 2.

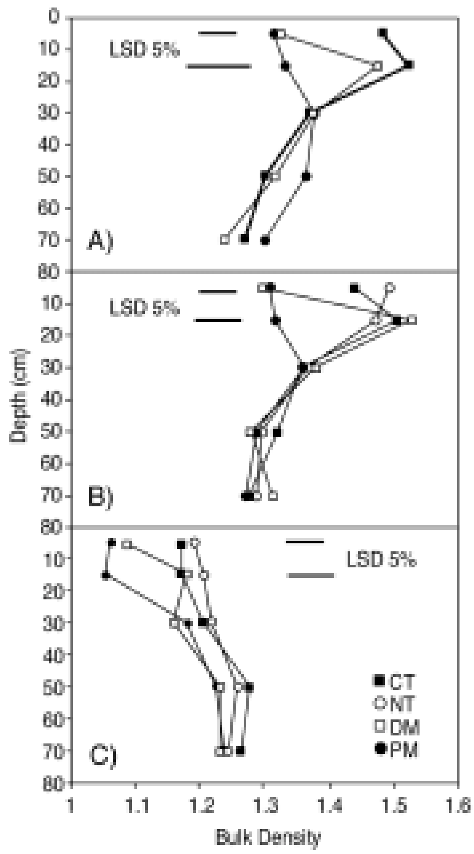


Fig. 4. Profiles of soil bulk density with four tillage systems, A: Site 1, 1990; B: Site 1, 1991; C: Site 2, 1991;
■ CT, conservation tillage with 0.2 kg m^{-2} dry matter mulch;
○ NT, zero tillage without mulch;
□ DM, disking at 7-10 cm depth;
● PM, disk ploughing at 15-20 cm depth.

contrast, other treatments had appreciably denser and deeper colonization in 1991 than in 1990. Frequency in the 0.1-0.2 m soil layer was highest in treatment PM, where this layer was loosened by tillage. These results suggests that the dry month of July 1990 caused a slower progression of roots and wet front regardless of treatments, whereas rains in 1991 allowed faster progression of the root system. Colonization was denser at site 2 than at site 1 in 1991, probably because of the natural shrinking and cracking activities of the black soil (higher clay content), which allowed roots to penetrate along cracks. Consistently, differences among treatments were low at site 2 (insignificant differences among treatments). Overall, these results suggest that soil colonization by roots was closely linked to changes over time in soil water content, with a positive effect of wetting at site 1 and an effect of alternate wetting and drying at site 2, but that tillage treatments did not strongly influence root system characteristics.

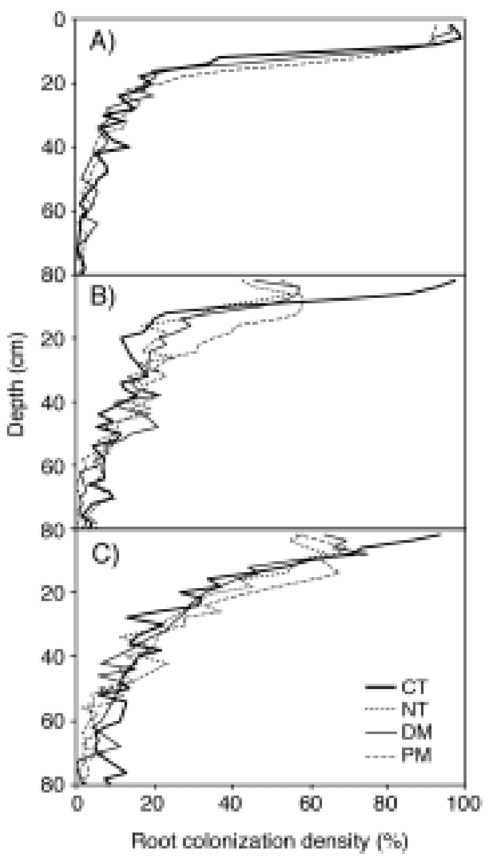


Fig. 6. Root contact frequency in 2x2 quadrats on a root map, plotted against soil depth. A: Site 1, 1990; B: Site 1,1991; C: Site 2, 1991.

In general, CT had a sparser and more clumped root system, compared with those for treatments DM and PM. Disking had a positive effect on root density in the 0.1-0.2 m layer at both sites, consistent with lower bulk density and penetrometer differences. On the contrary, high penetrometer resistance and bulk density only result in a slightly sparser colonization in treatment NT. Those effects on soil physical conditions were still significant three months after tillage, in contrast to other studies on tropical sandy soils, where tillage effects tended to disappear quickly (Chopart and Nicou 1976). Overall, differences in root system characteristics among treatments remained quite small (Tardieu 1988b). Root systems were less dense and shallower across sites and treatments, compared with root systems analyzed using the same method in European fields (Tardieu 1988a; Nicoullaud et al. 1992; Pellerin and Pages 1994). In particular, colonization of soil layers deeper than 0.4 m was particularly sparse in all treatments and rewetting of the 0.0-0.4 m soil layer was therefore particularly critical for plant water supply.

Crop Water Uptake During Dry Periods

Across sites and years, Eta during dry periods was highest in treatment CT, being approximately twice that of NT in 1991, where treatment DM resulted in intermediate ETa values. Consistent differences were observed during the dry periods analyzed at site 1 (La Tinaja) in 1990 and at site 2 (Campo Experimental) in 1991, although initial available soil water was highest at site 2. ETa rate, calculated as the ratio of total soil water depletion during a dry period to the duration of this period, was closely linked to the amount of available soil water at the beginning of the period studied (Fig. 7). For 1990, the two regression lines in the figure correspond, one to the first dry period during which plants had 8 to 10 leaves and the other to silking. The slope of this relationship was common to both periods, with a higher intercept at silking. This was probably due to the difference in leaf area index for the two periods and the correspondingly higher transpiration rates at silking. Interestingly, for both periods, treatments DM and CT belonged to the same relationship, suggesting that the higher ETa rates observed in treatment CT were linked to differences in water availability. Relationships between initial available water and ETa rate were also observed in 1991 at silking. In this case, common relationships applied to the three studied treatments at each site, but higher ETa rates were observed at site 2 (Campo Experimental) than at site 1 (La Tinaja), for a given amount of available water.

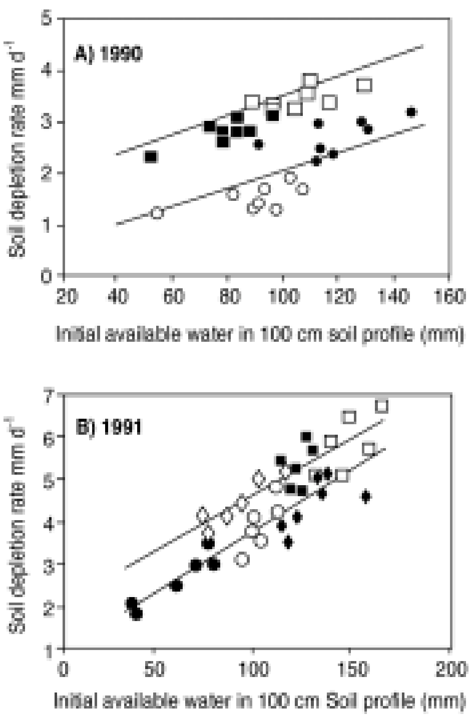


Fig. 7. Water depletion rate of soil during four dry periods, plotted against the amount of available water at the beginning of the studied period.
A: Site 1, 1990, ○ and ●, treatments DM and CT during the first dry period when maize plants had 8-10 appeared leaves. $y = 0.019x + 0.79$, $r^2 = 0.79$. ■ and □, treatments DM and CT during the second dry period with maize plants at silking. $y = 0.017x + 0.39$, $r^2 = 0.67$
B: Site 1 and 2, 1991 with plants at silking, ♦, ●, ○, treatments CT, NT and DM Site 1. $y = 0.029x + 0.90$, $r^2 = 0.87$; □, ◊, ■, treatments CT, NT, and DM Site 2. $y = 0.027x + 1.98$, $r^2 = 0.77$

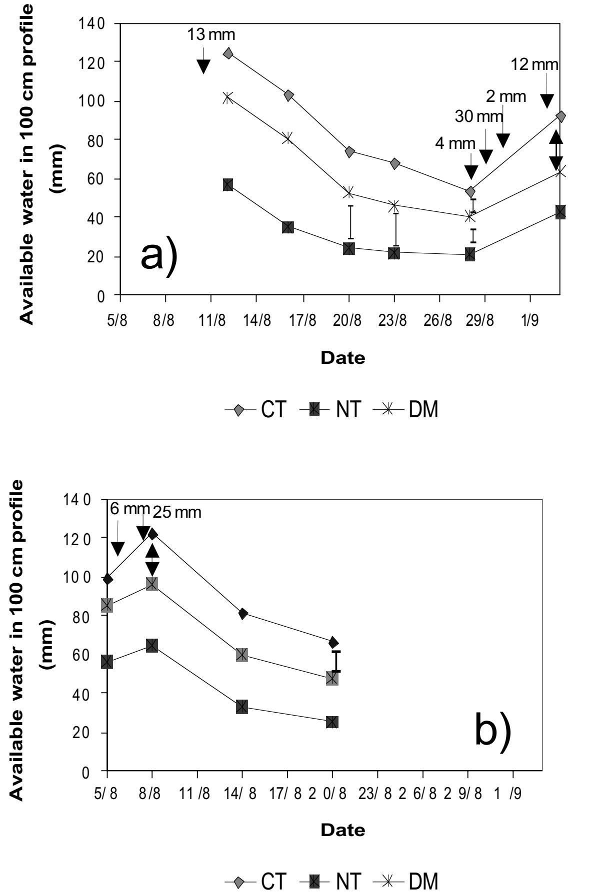


Fig. 8. Water available to the maize crop in the upper 100 cm of soil versus time during a period with little or no rainfall, as affected by land preparation treatments on two distinct soil types, Jalisco, Mexico, 1991. a) at La Tinaja (brown soil) site; b) at Campo Experimental (black soil) site.Crop water use and soil water storage from the previous dates were significantly different (p=0.05, Tukey test) between the two treatments.

A dynamic monitoring of soil moisture during dry spells of 12 to 16 days under both soil types (Fig. 8) revealed that throughout the period there was more available water and that there is a better crop water supply under CT than under NT or DM. At the end of the dry period differences between treatments in available water tended to be less important because of a greater crop water use under the CT treatment, where water was more abundant at the onset of the period. When a new wet period commenced, however, treatment differences favoring CT appeared again, because of differences in rainfall capture and storage. Since the curves of water availability with time after rainfall ceased are essentially parallel for the first 4 to 5 days (Fig. 8), this suggests that treatments did not induce differences in water usage by the crop during that period. This suggests too that crop water necessities are similar for all treatments. However, water uptake later began to differ, the NT treatment being the first and DM the second to show a reduction in uptake because of reduced soil water availability. This reduction could have important consequences. For example, with the NT treatment on brown soil (Fig. 8a), the crop virtually ceased using water during 8 days (08/21 to 08/29). With CT treatments, even though crop water use was slightly reduced, it never approached zero.

Indicators of Crop Water Use and Crop Water Status

For most dry periods considered there were significant differences in plant water potential, leaf temperature, and stomatal conductance (gs; Table 6). Plants from the CT treatments had consistently higher leaf water potentials, lower leaf temperatures, and higher stomatal conductance. Lowest leaf water potentials and highest leaf temperatures were found in DO (1990) and NT (1991); DM and PM treatments were intermediate for these traits. Where gs was observed on two dates during a dry spell in 1991, it declined from the first to the second measurement, and treatment differences increased as time progressed, showing a growing advantage of CT over other treatments.

Table 6. Stomatal conductance (gs), water potential (y) and surface temperature (Tf) of the leaves of maize grown under different tillage treatments, during dry periods of varying duration in different experimental locations, 1990 and 1991, Jalisco, Mexico.

	Tillage treatments[1]					
	CT	**NT**	**DO**	**DM**	**PM**	**SD[2]**
La Tinaja 1990 (07/27-08/10) (brown soil)						
gs (cm/s) on 08/06	0.22 a		0.16b	0.14b	0.18b	**
Tf (°C) on 08/06	32.5		33.2	33.7	33.5	NS
y (MPa) on 08/06	1.47		1.42	1.48	1.45	NS
Cuatro Caminos 1990 (black soil)						
gs (cm/s) on 08/16	0.54		0.44	0.41	0.37	NS
Tf (°C) on 08/16	28.6		28.8	29.7	30.5	NS
y (MPa) on 08/16	1.47		1.50	1.54	1.56	NS
La Tinaja 1991 (08/12-08/29) (brown soil)						
gs1 (cm/s) on 08/18	0.46a	0.22c		0.38b	0.41b	**
gs2 (cm/s) on 08/24	0.27a	0.09c		0.16b	0.20b	**
Tf (°C) On 08/24	27.6	29.0		28.6	27.7	NS
y (MPa) on 08/24	0.98a	1.50b		1.04a	0.99a	**
Campo Experimental 1991 (08/08-08/20) (black soil)						
gs1 (cm/s) on 08/14	0.44a	0.33b		0.36b	0.38b	*
gs2 (cm/s) on 08/20	0.39a	0.14c		0.25b	0.31ab	**
Tf (°C) on 08/20	30.4a	31.5b		31.3b	30.7a	*
y (MPa) on 08/20	1.19a	1.64c		1.46b	1.33b	**

1. CT = Conservation tillage; NT = no tillage; DO = light disking + no mechanical weed control; DM = idem; DO = with mechanical weed control; PM = Disk plowing.

2. ** Significant differences at 1%; * significant differences at 5%; NS = non-significant differences.

This illustrates that, for the situations where gs was low, there was real difficulty in meeting crop water needs (Bennett et al. 1986; Bolaños et al. 1993). In the CT treatment crop performance was less perturbed during dry periods because of a more adequate relation between supply and demand for water.

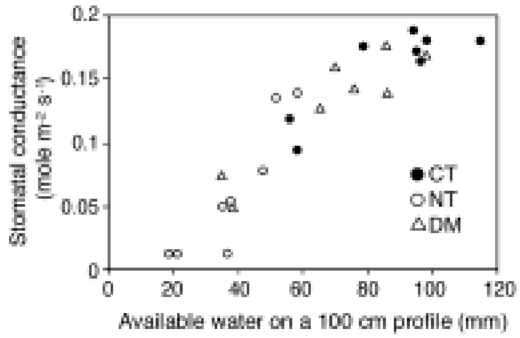


Fig. 9. Stomatal conductance at 12 o'clock plotted against available water for two dates of a dry period in 1991 in both site 1 (08/18 and 08/24) and site 2 (08/14 and 08/20). Each point, couple value of stomatal conductance and available water corresponding to one day in one experimental plot.

Stomatal conductance on a given day was also closely related to the amount of available water on the same day (Fig. 9), regardless of treatments and sites. A unique relationship accounted for variability in stomatal conductance within a treatment and for differences between treatments. As a consequence, the relationship observed between calculated ETa and available water was probably linked to stomatal control, itself linked to soil water status (Muchow and Sinclair 1991). Joint analyses of stomatal behavior and soil depletion suggest that observed differences among treatments could not be linked to root system water uptake capacity. When plant water deficits result from an inefficient root system, stomatal conductance in the corresponding plot decreases before that in the control treatment. Because soil water depletion is slower in plots of plants with inefficient root systems, soil water contents are higher than those in control plots after a few days (Tardieu et al. 1992b). Thus, a negative correlation is normally observed between stomatal

Table 7. Flowering dates and the anthesis-silking interval (ASI) as affected by different tillage treatments and location, 1990-1991, Jalisco, Mexico.

	Tillage treatments[1]					
	CT	NT	DO	DM	PM	SD[2]
La Tinaja 1990 (dry zone, brown soil)						
Anthesis (d)	55.0		54.8	55.0	55.3	NS
Silking (d)	57.0		57.8	58.8	57.0	NS
ASI (d)	2.0a		3.3ab	3.8b	2.8ab	*
Cuatro Caminos 1990 (dry zone, black soil)						
Anthesis (d)	57.0		57.3	57.3	57.5	NS
Silking (d)	58.5a		61.3b	61.5b	60.5ab	*
ASI (d)	1.5a		4.0b	4.3b	3.0ab	**
Campo Experimental 1991 (dry zone, black soil)						
Anthesis (d)	56.3	55.5		56.3	55.8	NS
Silking (d)	59.0a	61.3b		61.3b	59.3a	*
ASI (d)	2.8a	5.8b		5.0b	3.5a	**
San Isidro 1991 (humid zone, brown soil)						
Anthesis (d)	60.8	60.8		60.8	61.0	NS
Silking (d)	64.5	63.8		64.0	63.5	NS
ASI (d)	3.8	3.0		3.3	2.5	NS

1. CT = Conservation tillage; NT = no tillage; DO = light disking + no mechanical weed control; DM = idem; DO = with mechanical weed control; PM = Disk plowing.

2. ** Significant differences at 1%; * significant differences at 5%; NS = non-significant differences.

conductance and soil water reserve (the lowest stomatal conductance appearing in soils with the highest water potential). In our results stomatal conductance correlated positively with soil water availability, suggesting that differences in plant water uptake were not linked to root system characteristics. Differences in conductance and in depletion rates among treatments can therefore be accounted for by the ability of soil to store water, and not to differences in the root system's ability to take up water. Treatment CT, for example, which had highest conductances and ETa rates, had sparser root systems.

Anthesis-silking Interval

For the four location-years where this variable was measured, only the site in the wetter part of the zone (San Isidro 1991) failed to show significant treatment effects (Table 7). At the other sites in the drier part of the zone (La Tinaja 1990, Cuatro Caminos 1990, Campo Experimental 1991), treatment differences were significant for ASI when dry periods occurred before anthesis. At these sites ASI was smaller in CT and PM treatments than in treatments involving a maximum amount of cultivation. These differences paralleled those observed for water uptake during the dry periods before flowering. Smaller ASI could be equated with greater water uptake, a reduced level of plant water stress (Bolaños et al. 1993), an increase in current photosynthesis (Schussler and Westgate 1991; 1994), and an increase in kernels per plant and per unit area (Edmeades et al. 1993; Bolaños and Edmeades 1993). Delayed silking in treatments where water use was relatively less suggests that the production of assimilates at flowering was reduced by the direct effect of water stress on photosynthesis and that this affected the number of grains per plant and per unit land area (DuPlessis and Dijkhuis 1967; Westgate and Boyer 1986; Westgate 1997). At La Tinaja 1990, differences due to treatments were smaller, illustrating the reduced impact of the dry period.

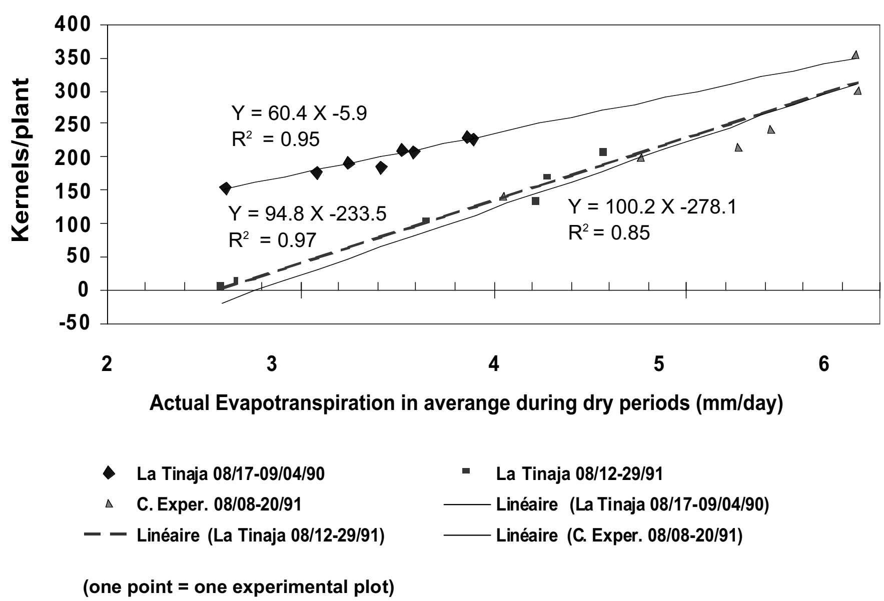


Fig. 10. Kernels per plant versus actual crop evapotranspiration during dry periods that coincided with the preflowering and flowering periods in 1990-91, Jalisco, Mexico.

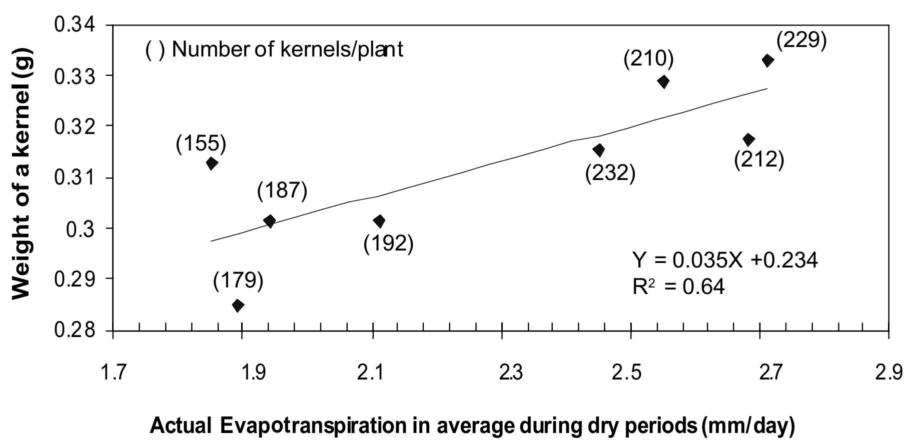
Effects on Yield Components

There was a strong correlation between crop ETa during dry periods before flowering and the number of grains per plant (Fig. 10) in each of the three locations where long dry periods occurred (La Tinaja 1990, r+ = 0.95; La Tinaja 1991, r+ = 0.97; Campo Experimental 1991, r+ = 0.85). This correlation was similar for both types of soil in 1991 but differed by soil type at La Tinaja 1990, when ETa was reduced by cloudy weather and small rainfall events were more numerous. Consequently, ASI was relatively small and there was little barrenness (Bolaños and Edmeades 1993).

A significant correlation was also observed (r+ = 0.64) between crop ETa during a dry period post-flowering and kernel weight at La Tinaja 1990 (Fig. 11). The diminished uptake of water reduced grain yield, as expressed in both lower weights per kernel and fewer grains per plant at this site. Again, a reduction in plant water status appeared to explain this (Grant et al. 1989; NeSmith and Ritchie 1992; Otegui et al. 1995).

These relationships demonstrate the impact of water availability around flowering on yield components, and underscore the importance of this period in yield determination (Claasen and Shaw 1970; Grant et al. 1989) on both soil types in the drier parts of the zone. Thus, although water uptake is not the only determinant of grain yield in these environments, in the lower rainfall areas of the zone it emerged as a very important yield determinant. Strong interactions between water availability and mineral uptake, especially the more soluble nutrients such as N and K, can also be expected (Bennett et al. 1986), but additional studies will be necessary to determine their respective importance in these environments. In dry zones, CT could have important advantages deriving from its superior water storage and availability, which allow plants to maintain photosynthesis longer during dry spells. The effects on grains per plant and grain weight could be large and significantly increase grain yield.

In the wetter zone, the relatively few differences observed due to treatments were not explained by water use but rather to factors such as those affecting crop nutrition. Treatment differences favoring PM were observed in root growth, especially in the upper 40 cm of the profile. Although it seems unlikely these could account for water uptake, they were possibly large enough to increase nutrient uptake, especially of lightly-moving elements such as P, under wetter conditions (Nielsen et al. 1998).



(one point = one experimental plot)

Fig. 11. Weight per kernel versus actual evapotranspiration during a dry spell during grain filling, 09/19-10/04/1991, at site 1, La Tinaja (Brown soil), Jalisco, Mexico.

Conclusions

This study showed the potential advantage of CT for semiarid zones, and in particular for western Mexico. In the driest areas (400-500 mm per crop cycle), this technique allowed a better capture and utilization of rainwater. Conservation tillage methods, and particularly mulching, can increase water storage and significantly reduce runoff in climates with intense and relatively rare rainfall events. Water use by plants may essentially depend on the amount of water stored in the soil. Water uptake during dry periods is therefore greater and more uniform over time with CT than with traditional land preparation methods. Joint analyses of changes in stomatal conductance and soil water content indicate that differences were probably not linked to the ability of root systems to take up water—consistent with in situ analysis of root systems by root mapping—but may have been more related to soil water availability at the beginning of the dry period. The consequences of better ETa on maize grain production, and in particular on kernel number per unit area, are especially obvious when dry spells occur around flowering, and in this study CT increased grain yield by 30-100% in drier parts of the study zone.

Clearly CT, even with low use of crop residue mulching (0.2 kg/m^2), has considerable potential for adoption in these semiarid areas, once technical issues such as supply of appropriate machinery, weed control, and the competing use of the maize residue for forage have been resolved (Scopel and Chavez Guerra 1999). Even under wetter conditions (500-700 mm per cycle), CT resulted in acceptable yields that were marginally less than those for the PM treatment but similar to those for other land preparation treatments without any protecting mulch. Here the lower cost of CT should make it an attractive alternative, especially for farmers who have to contract tractor operations from off-farm sources. Additionally, the long-term effects of CT on productivity and soil physical conditions (reducing soil erosion, increasing soil organic matter content, modifying soil biological activities) should be considered in a general assessment of the technique (Scopel and Chavez Guerra 1999).

References

Affholder, F., E. Scopel, J. Madeira, and A. Capillon. 2001. Diagnosis of the productivity gap using a crop model. Methodology and case study of small-scale maize production in central Brazil. (Accepted in *Agronomie*)

Al-Darby, A.M., B. Lowery, and T.C. Daniel. 1987. Corn leaf water potential and water use efficiency under three conservation tillage systems. *Soil Tillage Res.* 9: 241-254.

Bennett, J.M., J.W. Jones, B. Zur, and L.C. Hammond. 1986. Interactive effects of nitrogen and water stress on water relations of field-grown corn leaves. *Agron. J.* 78:273-280.

Bolaños, J., and G.O. Edmeades. 1993. Eight cycles of selection for drought tolerance in lowland tropical maize. II. Responses in reproductive behavior. *Field Crops Res.* 31: 253-268.

Bolaños, J., G.O. Edmeades, and L. Martinez. 1993. Eight cycles of selection for drought tolerance in lowland tropical maize. III. Responses in drought-adaptive physiological and morphological traits. *Field Crops Res.* 31:269-286.

Bolaños, J., and G.O. Edmeades. 1996. The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize. *Field Crop Res.* 48: 65-80.

Casenave, A., and C. Valentin. 1991. Infiltration into sealed soils as influenced by gravel cover. *Soil Sci. Soc. Am. J.*, 56:1667-1673.

Chopart, J.L. 1990. Variable effects of soil cultivation on maize production in the Ivory Coast as a function affecting water supply. In Climatic Risk in Crop Symposium Proc., Jul. of 1990, 104-105.

Chopart, J.L., and D. Kone. 1985. Influence de differentes techniques de travail du sol sur l'alimentation hydrique du mais et du cotonnier en Cote d'Ivoire. *Agronomie Tropicale* 40 (3): 223-229.

Chopart, J.L., and R. Nicou. 1976. Influence du labour sur le développement radiculaire de differentes plantes cultivées au Sénégal, consequences sur l'alimentation hydrique. *Agronomie Tropicale* 31(1): 7-28.

Claassen, M.M., and R.H. Shaw. 1970. Water deficit effects on corn: II. Grain components. *Agron. J.* 62:652-655.

Duley, F.L., and L.L. Kelly. 1939. Effect of soil type, slope, and surface conditions on intake of water. Nebr. Agric. Exp. Stn. Res. Bull. No 112.

DuPlessis, D.P., and F.J. Dijkhuis. 1967. The influence of time lag between pollen shedding and silking on the yield of maize. *S. Afric. J. Agric. Sci.* 10:667-674.

Edmeades, G.O., J. Bolaños, M. Hernández, and S. Bello. 1993. Underlying causes for silk delay in lowland tropical maize. *Crop Sci.* 33: 1029-1035.

Gajri, P.R., V.K. Arora, and S.S. Prihar. 1992. Tillage management for efficient water and nitrogen use in wheat following rice. *Soil Tillage Res.* 24: 167-182.

Grant, R.F., B.S. Jackson, J.R. Kiniry, and G.F. Arkin. 1989. Water deficit timing effects on yield components in maize. *Agron J.* 81: 61-65.

Hamblin, A.P. 1984. The effect of tillage on soil surface properties and the water balance of a xeralfic alfisol. *Soil Tillage Res.* 4: 543-559.

Hillel, D., and W.R. Gardner. 1970. Transient infiltration into crusted-topped profiles. *Soil Sci.* 109: 69-76.

Lal, R., P.R. Maurya, and S. Osei-Yeboah. 1978. Effects of no-tillage and plowing on efficiency of water use in maize and cowpea. *Exp. Agric.* 14(2): 113-120.

Mengel, D.B., and S.A. Barber. 1974. Development and distribution of the corn root system under field conditions. *Agron. J.* 66:341-344.

Muchow, R.C., and T.R. Sinclair. 1991. Water deficits on maize yields under current and greenhous climates. *Agron. J.* 83:1052-1059.

NeSmith, D.S., and J.T. Ritchie. 1992. Maize (*Zea mays* L.) response to a severe soil water-deficit during grain-filling. *Field Crops Res.* 29:23-35.

Nicoullaud, B., D. King, and F. Tardieu. 1994. Vertical distribution of maize roots in relation to permanent soil characteristics. *Plant and Soil* 159:245-254.

Nielsen, K.L. C.R. Miller, D. Beck, and J.P. Lynch. 1998. Fractal geometry of root systems: field observations of contrasting genotypes of common bean (*Phaseolus vulgaris* L.) grown under different phosphorus regimes. *Plant & Soil* 206: 2, 181-190.

Ogunremi, L.T., R. Lal, and O. Babaloa. 1986. Effects of tillage methods and water regimes on soil properties and yield of lowland rice from a sandy loam soil in southwest Nigeria. *Soil Tillage Res.* 6:223-234.

Ojeniyi, S.O. 1986. Effects of zero-tillage and disk plowing on soil water, soil temperature and growth and yield of maize (*Zea mays* L.). *Soil Tillage Res.* 7:173-182.

Osuji, G.E. 1984. Water storage, water use and maize yield for tillage systems on a tropical alfisol in Nigeria. *Soil Tillage Res.* 4:339-348.

Otegui, M.E., F.H. Andrade, and E.E. Suero. 1995. Growth, water use, and kernel abortion of maize subjected to drought at silking. *Field Crops Res.* 40:87-94.

Pellerin S, and L. Pages. 1994. Evaluation of parameters describing the root system architecture of field grown maize plants. *Plant and Soil* 164:155-167.

Schussler, J.R., and M.E. Westgate. 1991. Maize kernel set at low water potential: II. Sensitivity to reduced assimilates at pollination. *Crop Sci.* 31:1196-1203.

Schussler, J.R., and M.E. Westgate. 1994. Increasing assimilate reserves does not prevent kernel abortion at low water potential in maize. *Crop Sci.* 34:1569-1576.

Scopel, E., Chavez Guerra, E. 1999. Impacto agronómico de Labranza de Conservación sobre productividad de maíz de temporal en el Occidente de México. XLV PCCMCA, 12/16 of April 1999, Guatemala City, Guatemala.

Sebillotte, 1989. Approaches of the on-farm agronomist: illustrated methodological considerations. Development oriented research on agrarian systems project, Kasetsart University, 36 p.

Steiner, J.L. 1989. Tillage and residue effects on evaporation from soils. *Soil Sci. Soc. Am. J.* 53, 911-916.

Steiner, J.L. 1994. Crop residue effects on water conservation. In P.W. Unger (ed.), *Managing Agricultural Residues,* 41-76. Lewis Pub. Boca Raton, Fl., USA.

Tardieu, F. 1988a. Analysis of spatial variability of maize root density. I- Effects of wheel compaction on spatial arrangement of roots. *Plant and Soil* 107: 259-266.

Tardieu, F., 1988b. Analysis of spatial variability of maize root density. III- Effects of wheel compaction on water extraction. *Plant and Soil* 109: 257-262.

Tardieu, F., and H. Manichon. 1987. Etat structural, enracinement et alimentation hydrique du maïs. II-Croissance et disposition spatiale du système racinaire. *Agronomie* 7 (3): 201-211

Tardieu, F., J. Zhang, and W.J. Davies. 1992. What information is conveyed by an ABA signal from maize roots in drying field soil? *Plant, Cell and Environment* 15:185-191.

Tardieu, F., J. Zhang, N. Katerji, O. Bethenod, S. Palmer, and W.J. Davies. 1992. Xylem ABA controls the stomatal conductance of field-grown maize subjected to soil compaction or soil drying. *Plant, Cell and Environment* 15:193-197.

Unger, P.W., and T.M. Mc Calla. 1980. Conservation tillage systems. *Adv. Agron.* 33:1-57.

Unger, P.W., and J.J. Parker. 1976. Evaporation reduction from soil with wheat, sorghum, and cotton residue. *Soil Sci. Soc. Am. J.* 40: 938-942.

Westgate, M.E. 1997. Physiology of flowering in maize: identifying avenues to improve kernel set during drought. p. 136-141. In G.O. Edmeades, M. Bänziger, H.R. Mickelson and C.B. Peña-Valdivia (eds.) *Developing Drought and Low-N Tolerant Maize*. Mexico, D.F.: CIMMYT.

Westgate, M.E., and J.S. Boyer. 1986. Reproduction at low silk and pollen water potentials in maize. *Crop Sci.* 26:951-956.

Wey, J., R. Oliver, H. Manichon, and P. Siband. 1998. Analysis of local limitations to maize yield under tropical conditions. *Agronomie* 18:545-561.

Wilhelm, W.W., J.S. Schepers, L.N. Mielke, J.W. Doran, J.R. Ellis, and W.W. Stroup. 1987. Dryland maize development and yield resulting from tillage and nitrogene fertilization practices. *Soil Tillage Res.* 10: 167-179.

Effects of Conservation Tillage on Water Supply and Rainfed Maize Production in Semiarid Zones of West-Central Mexico

Eric Scopel[a*], François Tardieu[b], Gregory Edmeades[c], and Michel Sebillotte[d]

[a] Agronomist, CIRAD-CA, GEC program, BP 5035, 34032 Montpellier, FRANCE
[b] Agro-physiologist, LEPSE, INRA/ENSAM, 9 place Viala, 34000 Montpellier, FRANCE
[c] Agro-physiologist, Pioneer Hi Bred, Hawaii
[d] Agronomist, INRA, 147 rue de l'Université, 75338 Paris, FRANCE

NRG
Natural Resources Group

Paper 01-01

[*] Corresponding author

CIMMYT® (www.cimmyt.org) is an internationally funded, nonprofit, scientific research and training organization. Headquartered in Mexico, CIMMYT works with agricultural research institutions worldwide to improve the productivity, profitability, and sustainability of maize and wheat systems for poor farmers in developing countries. It is one of 16 food and environmental organizations known as the Future Harvest Centers. Located around the world, the Future Harvest Centers conduct research in partnership with farmers, scientists, and policymakers to help alleviate poverty and increase food security while protecting natural resources. The centers are supported by the Consultative Group on International Agricultural Research (CGIAR) (www.cgiar.org), whose members include nearly 60 countries, private foundations, and regional and international organizations. Financial support for CIMMYT's research agenda also comes from many other sources, including foundations, development banks, and public and private agencies.

Future Harvest® builds awareness and support for food and environmental research for a world with less poverty, a healthier human family, well-nourished children, and a better environment. It supports research, promotes partnerships, and sponsors projects that bring the results of research to rural communities, farmers, and families in Africa, Asia, and Latin America (www.futureharvest.org).

Correct citation: Scopel, E., F. Tardieu, G.O. Edmeades, and M. Sebillotte. 2001. *Effects of Conservation Tillage on Water Supply and Rainfed Maize Production in Semiarid Zones of West-Central Mexico.* NRG Paper 01-01. Mexico, D.F.: CIMMYT.
Abstract: This study analyzes the potential of conservation tillage (CT) for improving maize productivity under a range of soil and rainfall conditions in a semiarid zone of West-Central Mexico, evaluating the consequences of tillage practices on the crop's ability to take up and store water, on evapotranspiration, on crop physiology, and on grain yield, under cropping systems typical of small-scale farmers. Even with low use of crop residue mulching (0.2 kg/m^2), CT has considerable potential for adoption in these areas, once technical issues such as supply of appropriate machinery, weed control, and the competing use of the maize residue for forage have been resolved. Even under wetter conditions, CT resulted in acceptable yields.
ISSN: 1405-2830.
AGROVOC descriptors: Maize; Mexico; Statistical analysis; Yield components; Rain; Soil testing; Soil water retention; Tillage; Water conservation; Zea mays
AGRIS category codes: F06 Irrigation
P10 Water Resources and Management
Dewey decimal classification: 631.51

Printed in Mexico.

Contents

Tables ... iv

Figures ... v

Introduction ... 1

Materials and Methods ... 2

Sites and Experimental Design ... 2

Statistical Analyses ... 5

Results and Discussion ... 5

Rainfall at Each Site ... 5

Yield and Yield Components ... 5

Effect of Tillage Treatments on Maize Production ... 7

Soil Water Capture Capacity ... 7

Root System Differentiation ... 10

Crop Water Uptake During Dry Periods ... 11

Indicators of Crop Water Use and Crop Water Status ... 13

Anthesis-silking Interval ... 15

Effects on Yield Components ... 16

Conclusions ... 17

Tables

Table 1. Sites of experiments to determine the potential of conservation tillage for improving maize productivity in the municipality of Venustiano Carranza, Jalisco state, western Mexico, 1990-91. 3

Table 2. Rainfall characteristics for each experimental location in 1990 and 1991, Jalisco, Mexico. 4

Table 3. Maize yields and yield components for each experimental location, 1990 and 1991, Jalisco, Mexico. 8

Table 4. Moisture front depth in the soil profile at the beginning of the cycle for four tillage treatments at two sites, Jalisco, Mexico, 1991. 9

Table 5. Available water at the beginning and at the end of a rainy period and additional water stored in the profile during this period for different tillage treatments at two sites in Jalisco, Mexico, during 1990-1991. 9

Table 6. Stomatal conductance (gs), water potential (y) and surface temperature (Tf) of the leaves of maize grown under different tillage treatments, during dry periods of varying duration in different experimental locations, 1990 and 1991, Jalisco, Mexico. 13

Table 7. Flowering dates and the anthesis-silking interval (ASI) as affected by different tillage treatments and location, 1990-1991, Jalisco, Mexico. 14

Figures

Figure 1. Distribution of rainfall during the three growing periods, and positions of studied dry and rainy periods. 5

Figure 2. Principal components analysis of grain yield by yield components, ear morphology and biomass at flowering in the first plan (axes 1-2) projection, for all the treatments of four maize trials grown in 1990-91 in farmers' fields, Jalisco, Mexico. 6

Figure 3. Profiles of soil water content at the beginning and end of a rainy period from 28 August to 3 September 1991. 7

Figure 4. Profiles of soil bulk density with four tillage systems. 10

Figure 5. Profiles of penetrometer resistance with four tillage systems. 10

Figure 6. Root contact frequency in 2 x 2 quadrats on a root map, plotted against soil depth. 11

Figure 7. Water depletion rate of soil during four dry periods, plotted against the amount of available water at the beginning of the studied period. 12

Figure 8. Water available to the maize crop in the upper 100 cm of soil versus time during a period with little or no rainfall, as affected by land preparation treatments on two distinct soil types, Jalisco, Mexico, 1991. 12

Figure 9. Stomatal conductance at 12 o'clock plotted against available water for two dates of a dry period in 1991 in both site 1 (08/18 and 08/24) and site 2 (08/14 and 08/20). 14

Figure 10. Kernels per plant versus actual crop evapotranspiration during dry periods that coincided with the preflowering and flowering periods in 1990-91, Jalisco, Mexico. 15

Figure 11. Weight per kernel versus actual evapotranspiration during a dry spell during grain filling, 09/19-10/04/1991, at site 1 La Tinaja (Brown soil), Jalisco, Mexico. 16