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Techniques for controlling soil crusting and its effect on corn emergence and production

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Abstract

Soil crusting is a serious problem in numerous irrigated soils of Aragon. It reduces water infiltration rate, seedling emergence and crop establishment, and enhances runoff and soil erosion. This paper analyses the efficiency of soil conservation practices (direct drilling and mulching) and chemical amendments (gypsum) on the control of soil crusting, and its effect on seedling emergence and corn production. The experiments were carried out in Sierra de Luna (Zaragoza) in a soil prone to crusting. The experimental design was a randomised complete block with six treatments and three replications: T1 (sowing and several irrigations until emergence, a practice known as «aguacivera» in Aragon; considered as the control treatment), T2 (sowing and delayed irrigation until post-emergence), T3 (direct drilling over nearly bare soil), T4 (direct drilling over legumes), T5 (T1 + gypsum), and T6 (T2 + gypsum). In all the treatments, except for T1 and T5, irrigation was delayed until post-emergence. Measurements were made on plant emergence, penetration resistance of the crust, final infiltration rate and corn production. All variables were significantly affected by the treatments. T6 was the most effective treatment in reducing soil crusting and enhancing water infiltration into the soil, whereas both T6 and T2 were the most effective at enhancing seedling emergence and corn production. The «aguacivera» treatments (T1 and T5) induced the highest crusting and emergence reduction and, together with T3, they were the least productive, whereas the direct drilling treatments (T3 and T4) followed an intermediate pattern. For crusting reduction, treatment T4 was more effective than treatment T3. The addition of gypsum coupled to a delay in irrigation until corn emergence was thus the most effective treatment of those tested in this work to reduce soil crusting.

Key words: infiltration, soil conservation practices, direct drilling, gypsum, irrigation, legumes.

Resumen

Técnicas de control del encostramiento de los suelos y su efecto en la emergencia y producción de maíz

El encostramiento del suelo es un problema serio en muchos de los regadíos aragoneses: reduce la infiltración, aumenta la escorrentía y erosión y reduce la emergencia y producción de los cultivos. Este trabajo evaluó la eficiencia del laboreo de conservación (siembra directa, acolchado) y de enmiendas químicas (yeso) para minimizar el encostramiento y su efecto en la emergencia y producción de maíz. El estudio se realizó en Sierra de Luna (Zaragoza), mediante un diseño experimental de bloques al azar con seis tratamientos y tres repeticiones: T1 (siembra y riegos hasta nascencia, conocido como «aguacivera» en Aragón, y considerado como control), T2 (siembra y retraso de riegos hasta después de nascencia), T3 (siembra directa sobre suelo casi-desnudo), T4 (siembra directa sobre leguminosas), T5 (T1 + yeso), y T6 (T2 + yeso). En todos los tratamientos, excepto T1 y T5, se retrasaron los riegos hasta después de nascencia. El número de plantas emergidas, el grado de encostramiento, la tasa de infiltración y la producción de maíz fueron determinados. Todas las variables fueron significativamente afectadas por los tratamientos. El T6 fue el más efectivo en reducir el encostramiento y favorecer la infiltración. Los tratamientos T2 y T6 fueron los más efectivos en favorecer la emergencia y producción del maíz. Los tratamientos T1 y T5 fueron los mayores inductores de encostramiento y de reducción de emergencia, y junto al T3 los menos productivos. Los tratamientos de siembra directa tuvieron en general un comportamiento intermedio. El T4 fue más efectivo que el T3 para reducir el encostramiento. La adición de yeso unido a un retraso del riego hasta después de nascencia fue el tratamiento más efectivo de los evaluados en este trabajo para reducir el encostramiento del suelo.

Palabras clave: infiltración, laboreo de conservación, siembra directa, yeso, riego, leguminosas.

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Introduction

Soil crusting is a serious problem in many irrigated soils of the Middle Ebro River Basin (Amezketa and Aragües, 2000). Most soils of the Aragonese irrigated lands on the left side of the Ebro River are susceptible to chemical dispersion of soil colloids and, therefore, to crusting when they receive waters of very low electrical conductivity (EC), such as rainwater or the irrigation waters from the Pyrenèes. In addition, conventional farm management practices, where the soils are left bare for several months, followed by intensive tillage for land preparation and the subsequent breaking up of soil aggregates enhance surface sealing, and, on drying, crust formation (Cassel *et al.,* 1995). Soil crusting and the degree of crust compaction also depend on climatic factors such as wind, solar radiation and rainfall intensity (Gimenez *et al.,* 1992). If crusts develop before seedling emergence, their high mechanical resistance causes poor stand establishment and may reduce crop yields. Questionnaires completed by several Aragonese irrigators revealed that soil crusting reduced crop emergence by 20-30% and production by up to 50% (Amezketa and Aragües, 2000). Cassel *et al.* (1995) observed that crusts induced by intensive tillage reduced corn emergence up to 90%. Surface crusts also reduce water infiltration, and soil water recharge of the crop rooting zone, and enhance surface runoff on steep soils and, therefore, soil erosion.

To prevent or minimise crop yield reductions, the farmers break mechanically the soil crusts, perform frequent irrigations, and resow the fields, therefore increasing the production costs. Nevertheless, Cassel *et al.* (1995) reported that the mechanical disruption of the crusts can damage the seeds and young plants by crushing or uprooting them. Moreover, the improved infiltration promoted by the mechanical rupture of the crust is temporary on bare soils, since it reforms after each rainfall.

Irrigation management in soils susceptible to crusting is especially difficult. It is important to avoid pooling that can be harmful to sensitive plants such as onions at the time of emergence, as well as to avoid consolidation of the crust due to soil drying (Porta *et al.,* 1994). Although sprinkler irrigation can damage the structure of bare soils, its great advantage over flooding is that light and frequent irrigation can be applied to soft the crust and enhance emergence. Moreover, frequent irrigations by flooding until crop emergence (known as «aguacivera» in Aragon) enhance soil crusting and produce crusts thicker than normal.

Soil conservation practices and the addition of chemical amendments such as gypsum to the soil surface are some of the techniques aimed to minimise soil crusting. Conservation tillage practices are less aggressive to the soil than the traditional methods. They reduce the cultivation operations and the traffic of heavy equipment over the plots, and maintain at least 30% of the soil surface covered by crop residues. Among the different types of soil conservation practices, «no-tillage or direct drilling» is distinguished by (i) the chemical control of weeds before drilling, (ii) drilling as the only cultivation practice that disrupts the soil and (iii) maintaining 70 to 90% plant or residue cover on the soil surface. Several authors have shown the positive effects of no-tillage or direct drilling, such as reducing or impeding soil crusting (Angers *et al.,* 1993), increasing water infiltration into soil (Carter and Steed, 1992), enhancing seedling emergence and crop production (Cassel *et al.,* 1995), increasing soil aggregate stability (Prove *et al.,* 1990) and reducing runoff and soil erosion (Wollenhaupt *et al.,* 1995).

Addition of chemical amendments is recommended in soils susceptible to chemical dispersion of soil colloids. The dissolved gypsum releases calcium, slightly increasing the EC and reducing the sodium adsorption ratio (SAR) of the soil solution. Both mechanisms minimise the chemical dispersion and stabilise the soil aggregates. Moreover, the gypsum left over the soil surface partially protects the surface aggregates against the disruptive effects of water drops and wind, and interferes mechanically with crust formation.

The main objective of this work was to evaluate the efficiency of (i) soil conservation practices, such as direct drilling and mulching, and (ii) the addition of chemical amendments such as gypsum, in controlling soil crusting. The effect of conventional management practices in soil crusting was also investigated. The specific objective was to analyse the effects of these treatments on soil physical properties, seedling emergence and corn production.

Materials and methods

The study was conducted during the year 2000 in a crust-prone plot located in Sierra de Luna (Bardenas I irrigation district, Zaragoza, Spain). The electrical conductivity (EC) and the sodium adsorption ratio (SAR) of the 1:5 soil extract were, respectively, 0.5 dS m^{-1} and 0.3 (mmol $L^{-1})^{0.5}$, indicating that the soil was

Table 1. Description of treatments

Treatment	Description
T1	Control (C): conventional farming system using practices typical of the study area: sowing the corn with mellow soil conditions («tempero»), and irrigate several times until emergence («aguacivera»).
T2	Sowing with mellow soil conditions («tempero»), and delayed irrigation until post-emergence, standard agricultural practices.
T3	Conservation tillage: direct drilling over nearly bare soil* (very little stubble remains from the previous crop; the covered surface was less than or equal to 30%); soil only altered by sowing; chemical control of re-growth and weeds before sowing.
T4	Conservation tillage: direct drilling over field pea. The pea was sown in December and maintained as a cover crop, acting as mulching, from December to April. Few days before sowing it was killed by applying a contact herbicide. Soil only altered by drilling practise.
T5	As T1 + gypsum (4 t ha^{-1}) applied over the surface immediately after sowing.
T6	As T2 + gypsum (4 t ha^{-1}) applied over the surface immediately after sowing.

* Although this treatment does not properly corresponds to direct sowing (the cover of the surface was less than 70%), it has been called in this manner because it was very similar to T4; the only difference was that in T4 direct drilling was over a pea crop, while in T3 it was over a nearly bare soil.

not affected by salinity or sodicity. The plot was divided into 18 subplots of size 30 m by 4 m. The experimental design was a randomised complete block with six treatments (Table 1) and three replications. Corn (*Zea mays* L.), Cecilia variety (cycle 600) was grown in all plots. The management practices and the inputs applied in the six treatments are shown in Table 2. In all treatments, sowing was done with mellow soil conditions («tempero»). The plots were independently flood-irrigated. During irrigation, the flow (L s^{-1}), the time required to irrigate the plot (min), and the volume of water (m^3) were measured.

Mined-gypsum of high purity (93%), 0-12 mm diameter (Table 3), with a predominance of coarse fraction (63% of the particles had a diameter larger than 0.5 mm, while only 5% were smaller than 50 mm) was broadcasted over the soil surface immediately after sowing. The dose was 4 t ha^{-1} applied with a manure spreader.

Soil and crop measurements

Throughout the growing season, soil moisture content, resistance to crust penetration or degree of crusting, seedling emergence and corn production were measured, and the soil infiltration rate was estimated from the irrigation characteristics by applying an empirical infiltration equation.

Precipitation and temperature were recorded daily at a weather station located 20 km from the experimental area (Ejea de los Caballeros). The annual precipitation in 2000 (554 mm) was above normal (475 mm), although the increase was mainly due to the rainfall falling between August and November. The rainfall was 47 mm between sowing and emergence and 391 mm between sowing and harvesting (Fig. 1). Shortly after that rainfall felt following sowing, the wind speed was 8-11 m s^{-1}, equivalent to 29-40 km h^{-1}.

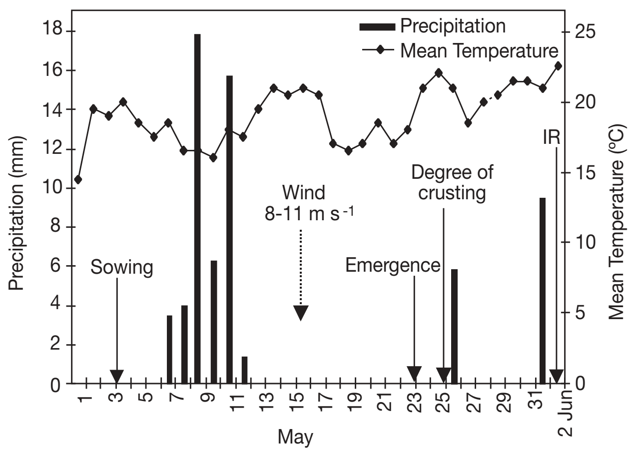

Figure 1. Daily precipitation and mean temperature recorded at the Ejea de los Caballeros weather station. Soil and crop measurements (% seedling emergence, degree of crusting and infiltration rate, IR) performed in the Sierra de Luna plot during May and at the beginning of June 2000 are also shown.

Table 2. Management practices used in each treatment and inputs applied per hectare

Date	Treatments					
	T1	T2	T3	T4	T5	T6
4 December 1999				Two passes with chisel Peas sowed at 100 kg ha^{-1}; One pass with harrow plow		
15 January 2000	Two crossed passes with chisel for land preparation	Two crossed passes with chisel for land preparation			Two crossed passes with chisel for land preparation	Two crossed passes with chisel for land preparation
24 February	Irrigation 1, R1	Irrigation 1, R1	Irrigation 1, R1	Irrigation of peas, R1	Irrigation 1, R1	Irrigation 1, R1
March	Treatment with chisel	Treatment with chisel			Treatment with chisel	Treatment with chisel
April	Furrowing, installation of irrigation system	Furrowing, installation of irrigation system	Furrowing, installation of irrigation system	Furrowing, installation of irrigation system	Furrowing, installation of irrigation system	Furrowing, installation of irrigation system
20 April			Application of herbicide (Gliphosphate 36%, 1.5 Lha^{-1})	Application of herbicide (Gliphosphate 36%, 1.5 L ha^{-1})		
24 April	Fertilising the plot with 330 kg ha^{-1} of 8-15-15	Fertilising the plot with 330 kg ha^{-1} of 8-15-15	Fertilising the plot with 330 kg ha^{-1} of 8-15-15	Fertilising the plot with 330 kg ha^{-1} of 8-15-15	Fertilising the plot with 330 kg ha^{-1} of 8-15-15	Fertilising the plot with 330 kg ha^{-1} of 8-15-15
2 May	Application of herbicide Primextra (metachloride 30% + atrazine 19%); 5 L ha^{-1}	Application of herbicide Primextra (metachloride 30% + atrazine 19%); 5 L ha^{-1}	Application of herbicide Primextra (metachloride 30% + atrazine 19%); 5 L ha^{-1}	Application of herbicide Primextra (metachloride 30% + atrazine 19%); 5 L ha^{-1}	Application of herbicide Primextra (metachloride 30% + atrazine 19%); 5 L ha^{-1}	Application of herbicide Primextra (metachloride 30% + atrazine 19%); 5 L ha^{-1}
3 May	Treatment with horizontal axle rotary cultivator and manual levelling. Sowing of corn: seed spacing: 70×14 cm Application of Lindano insecticide Irrigation R2 («Aguacivera»)	Treatment with horizontal axle rotary cultivator and manual levelling. Sowing of corn: Seed spacing: 70×14 cm Application of Lindano insecticide	Sowing of corn: seed spacing: 70×14 cm Application of Lindano insecticide	Sowing of corn: seed spacing: 70×14 cm Application of Lindano insecticide	Treatment with horizontal axle rotary cultivator and manual levelling. Sowing of corn: seed spacing: 70×14 cm Application of Lindano insecticide Application of gypsum (4 t ha^{-1}) Irrigation R2 («Aguacivera»)	Treatment with horizontal axle rotary cultivator and manual levelling. Sowing of corn: seed spacing: 70×14 cm Application of Lindano insecticide Application of gypsum (4 t ha^{-1})
15 May	Irrigation R3 («Aguacivera»),				Irrigation R3 («Aguacivera»),	
2 June 19 June	Irrigation R4: 750-1000 m^3 ha^{-1} Irrigation R5: 833-1000 m^3 ha^{-1} Top dress: Urea 600 kg ha^{-1}	Irrigation R2: 750-1000 m^3 ha^{-1} Irrigation R3: 833-1167 m^3 ha^{-1} Top dress. Urea 600 kg ha-1	Irrigation R2: 583-750 m^3 ha^{-1} Irrigation R3: 667-1250 m^3 ha^{-1} Top dress. Urea 600 kg ha^{-1}	Irrigation R2: 750-917 m^3 ha^{-1} Irrigation R3: 667-750 m^3 ha^{-1} Top dress. Urea 600 kg ha^{-1}	Irrigation R4: 750 m^3 ha^{-1} Irrigation R5: 750-1167 m^3 ha^{-1} Top dress. Urea 600 kg ha^{-1}	Irrigation R2: 917-1000 m^3 ha^{-1} Irrigation R3: 917-1083 m^3 ha^{-1} Top dress. Urea 600 kg ha^{-1}
3 July 17 July 27 July	Irrigation R6: 1083-1500 m^3 ha^{-1} Irrigation R7: 1167-1250 m^3 ha^{-1} Irrigation R8: 1167-1250 m^3 ha^{-1}	Irrigation R4: 917-1000 m^3 ha^{-1} Irrigation R5: 1000-1250 m^3 ha^{-1} Irrigation R6: 1000-1250 m^3 ha^{-1}	Irrigation R4: 667-1250 m^3 ha^{-1} Irrigation R5: 1083-1250m^3 ha^{-1} Irrigation R6: 1083-1250m^3 ha^{-1}	Irrigation R4: 833-1083 m^3 ha^{-1} Irrigation R5:1000-1250 m^3 ha^{-1} Irrigation R6:1000-1250 m^3 ha^{-1}	Irrigation R6: 833-1417 m^3 ha^{-1} Irrigation R7:1083-1250 m^3 ha^{-1} Irrigation R8:1083-1250 m^3 ha^{-1}	Irrigation R4: 833-1333 m^3 ha^{-1} Irrigation R5: 1083-1250 m^3 ha^{-1} Irrigation R6: 1083-1250 m^3 ha^{-1}
8 August 21 August	Irrigation R9: 1083-1167 m^3 ha^{-1} Irrigation R10: 1083-1167 m^3 ha^{-1}	Irrigation R7: 833-1083 m^3 ha^{-1} Irrigation R8: 1000-1083 m^3 ha^{-1}	Irrigation R7: 1000-1083m^3 ha^{-1} Irrigation R8: 1000-1083m^3 ha^{-1}	Irrigation R7: 917-1167 m^3 ha^{-1} Irrigation R8: 917-1083 m^{3}3 ha^{-1}	Irrigation R9:1000-1083 m^3 ha^{-1} Irrigation R10:1000-1083 m^3 ha^{-1}	Irrigation R7: 917-1083 m^3 ha^{-1} Irrigation R8: 917-1083 m^3 ha^{-1}
4 September	Irrigation R11: 1000-1083 m^3 ha^{-1}	Irrigation R9: 833-1083 m^3 ha^{-1}	Irrigation R9:1000-1083 m^3 ha^{-1}	Irrigation R9: 917-1083 m^3 ha^{-1}	Irrigation R11:1000-1083 m^3 ha^{-1}	Irrigation R9: 917-1000 m^3 ha^{-1}
8 November	Manual harvesting of corn in an area of 11.2 m^2	Manual harvesting of corn in an area of 11.2 m^2	Manual harvesting of corn in an area of 11.2 m^2	Manual harvesting of corn in an area of 11.2 m^2	Manual harvesting of corn in an area of 11.2 m^2	Manual harvesting of corn in an area of 11.2 m^2

Table 3. Physical and chemical properties of the mined-gypsum applied to the soil

Chemical characteristics		Granulometry	
Composition	*(%)*	*Particle size (mm)*	*(%)*
Combined H_2O	19.4	4-12	17.3
SO_3	43.3	2-4	21.1
CaO	31.6	1-2	15.2
MgO	0.4	0.5-1	9.1
Fe_2O_3	0.07	0.25-0.5	6.3
Purity (%)	93.0	0.125-0.250	4.9
*pH**	7.0	0.080-0.125	6.1
EC (dS m^{-1})*	2.2	0.050-0.080	15.6
		<0.050	5.0

* pH and EC measured in a saturated gypsum solution.

Degree of crusting (Resistance to crust penetration)

Resistance to crust penetration (Rc) was measured on 25 May in a plot of each treatment, except in T6, where two plots were measured. The measurements were made with a hand-held micropenetrometer (Eijkelkamp, IB model, section-cone of 0.25 cm^2, reading range 0-6 MPa). Approximately 15 measurements were made per seed row, corresponding to a total of 90 measurements per plot. The total number of micropenetrometer measurements presented in this work is 584.

Concurrent with the crust mechanical resistance measurements, soil water content at the 0-5 cm depth was determined gravimetrically by collecting soil samples in plant rows and oven drying at 105°C for 48 hours. Soil water content was expressed as percentage of dry soil.

Seedling emergence

Emerged corn plants were counted on 23 May, 20 days after sowing, in three transects (2 m long each) of each of the six rows of every plot. Emergence was expressed as (i) number of plants ha^{-1} and (ii) percentage of emerged plants, taking into account that the seed spacing for corn was 70 × 14 cm.

Soil infiltration rate

The soil infiltration rate (IR) was estimated from the irrigation characteristics on 2 June (one week after the crusting degree measurements) by applying the empirical Kostiakov equation, which corresponds to the classical infiltration equation in irrigation engineering (Walker and Skogerboe, 1987):

$$Z = K * t^a$$

where Z = cumulative infiltration (m), t = time that water is on the ground (minutes), and K and a are the empirical infiltration parameters. In this case a = constant among treatments, and corresponds to a value of 0.3 in soils similar to those of our experiment (Lecina *et al.*, 2001). During that irrigation, the decrease in water level height with time was measured. The K value was estimated for each plot from the advance of the wetting front (Walker and Busman, 1990), using iteratively a hydrodynamic simulation model for surface irrigation (Walker, 1993). The final infiltration rate (FIR) was estimated from the cumulative infiltration curve (Z) and applying a time of 360 minutes to the resulting equation.

Crop production

The number of corn plants per hectare and the production of grain were estimated on 8 November from two transects (4 m long each) in each of the two central rows of each plot, corresponding to a total of 11.2 m^2. Plants were counted and sampled, and the moisture content of grain (%), the wet-weight of grain (kg ha^{-1}) and the grain density (hectolitre-weight of grain, kg hL^{-1}) were measured. Grain production (kg ha^{-1}) was reported at 14% moisture. This production was estimated by a simple linear interpolation such that:

$$P_{(14\%)} = \frac{P_H \times (100 - H)}{86}$$

where $P_{(14\%)}$ = grain production with 14% moisture, $P_{(H)}$ = grain production with H% moisture, and H = percentage of humidity of harvested grain (%).

Statistical analysis

The results were analysed using Statgraphics *Plus for Windows* software (Statgraphics Plus for Windows, 1995). Analysis of variance (ANOVA) was carried out to analyse the effects of treatments and blocks on the studied variables. Where significant differences at P≤0.05 were found, a Duncan's multiple range test was conducted to separate mean values. Simple correlation analysis and the Spearman's rank correlation test were also employed. Statistical significance was reported at

Table 4. Mean absolute (No. plants ha^{-1}) and relative (% of seedlings emerged) values of corn seedling emergence. Values of No. of plants ha^{-1} with different letters were significantly different at P<0.05

Treatment	Corn seedlings emergence: No. plants ha^{-1}	n*	CV (%)	Emerged seeds (%)
T1	62,500 a	54	31.2	61.3
T2	78,824 c	51	18.9	77.3
T3	74,556 bc	54	21.6	73.1
T4	74,667 bc	51	23.8	73.2
T5	69,314 b	51	22.6	68.0
T6	78,185 c	54	15.6	76.7

* «n» corresponds to the number of 2 m long transects in which plants were counted. CV: coefficient of variation.

Table 5. Mean values of crust penetration resistance, and 0-5 cm depth soil water content, in the different treatments. Rc values with different letters were significantly different at P<0.05

Treatment	Water content (%)	Resistance to crust peneration: Rc (MPa)	n*	CV (%)
T1	8.3	5.95 a	90	2.4
T2	7.3	3.42 b	74	42.0
T3	7.4	4.64 c	81	25.1
T4	7.6	3.23 be	85	46.0
T5	8.2	5.19 d	75	6.5
T6	8.4	2.99 e	179	44.7

* «n» corresponds to the number of micropenetrometer measurements.

the 0.05 ($P<0.05$, *), 0.01 ($P<0.01$, **) and 0.001 ($P<0.001$, ***) probability levels.

Results

Seedling emergence

The number of emerged plants per hectare in the different treatments ranged from 62,500 to 78,824 (Table 4), with coefficients of variation (CV) between 16 and 31%. Seedling emergence varied significantly among treatments ($P<0.001$), but not by blocks ($P>0.05$). The interaction treatment × block (T × B) was not significant ($P>0.05$). Duncan's test established that the number of emerged plants increased in the order: T1<T5≤T3≤T4≤T6≤T2 (Table 4), so that T2 and T6 were the most effective treatments at enhancing emergence, while the «aguacivera» treatments (T5 and, in particular, T1) were the least efficient. Direct drilling treatments (T3 and T4) followed an intermediate pattern.

Nevertheless, seedling emergence was reduced in all treatments (Table 4). Thus, percentage of emerged plants was approximately 77% in the most effective treatments (T2 and T6), while it was 61% in the least effective (T1) treatment. Soil surface crusting and compaction and/or bird attacks could be responsible for the emergence reduction.

Degree of crusting (resistance to crust penetration)

Resistance to crust penetration (Rc) and 0-5 cm soil water content of the different treatments are shown in Table 5.

Resistance to crust penetration can only be compared among treatments if soil water contents are also taken into account, since the latter has an overriding effect on soil strength**.** Nevertheless, the soil water contents were very low and similar in all treatments (between 7.3 and 8.4%, not being significantly different, $P>0.05$), suggesting that differences in crust penetration resistance are only due to the treatments themselves. Resistance to crust penetration values ranged from 2.99 to 5.95 MPa, with CVs of the means varying between 2 and 45% (the least compacted treatments exhibited the greatest spatial variability).

All treatments exhibited some degree of crusting, which, on drying, acquired a high to very high soil surface compaction. The rain (47 mm) and wind (29-40 km h^{-1}) occurring shortly after sowing might induce that crusting.

Degree of soil crusting varied significantly among treatments ($P<0.05$), decreasing in the order: T1>T5>T3>T2≥T4≥ T6 (Table 5). Thus, treatment T6 was the most effective in reducing soil crusting, whereas the «aguacivera» treatments and particularly T1, were the ones inducing the highest degree of crusting. The «aguacivera» irrigation intensified the strength of the formed crust.

Gypsum application to the T6 (T2 + gypsum) plots was significantly effective in reducing surface crusting, compared to the crusting degree of the T2 plots. However, the differential effect of gypsum was not noticed on seedling emergence (No. of emerged plants in T6 and T2 were not significantly different, P>0,05), indicating that factors other than soil crusting affected crop emergence.

Direct drilling treatments (T3 and T4) exhibited, again, an intermediate behaviour with respect to the

Table 6. Mean *K* and final infiltration rate (FIR) values in the different treatments. K and FIR values with different letters within each column are significantly different at P<0.05

Treatment	K (m min^{-a})	(FIR, mm h^{-1})	n*	CV (%)
T1	0.016 ab	4.75 ab	3	6.3
T2	0.020 b	5.93 b	3	15.0
T3	0.014 a	4.06 a	3	25.7
T4	0.017 ab	5.04 ab	3	17.6
T5	0.014 a	4.15 a	3	12.4
T6	0.025 c	7.32 c	3	8.4

* «n» corresponds to the number of performed irrigation's evaluations.

remaining treatments. Direct drilling on field pea (T4) was significantly ($P<0.05$) more effective than drilling on nearly bare soil (T3) in reducing soil crusting.

Soil infiltration rate

Mean K values for the different treatments ranged from 0.014 to 0.025 m min^{-a}. Mean final infiltration rate (FIR) values ranged between 4.06 and 7.32 mm h^{-1} (Table 6), with CVs of the means varying between 6 and 26%. The analysis of variance established that both parameters varied significantly among treatments ($P<0.05$). The final infiltration rates decreased in the order: T6>T2≥T4≥T1≥T5≥T3. Treatment T6 was the most efficient in promoting the FIR. Concomitantly, T6 was the treatment with the lowest degree of crusting.

Crop production

Corn production in the different treatments is shown in Table 7. The intra-plots variability (CV of the mean grain production within each plot) ranged from 3 to 27%, while the variability among treatments fluctuated from 9 to 22%. Corn production ranged from 7,000 to 9,500 kg ha^{-1}, varying significantly among treatments (T) and blocks (B). The interaction T×B was also significant (Table 8), indicating that treatments influenced the corn production differently under each block and viceversa, each block affected corn yields differently under each treatment.

Two kinds of interaction are illustrated in Figure 2. The crossing lines indicate a crossover interaction. The higher than expected corn production for T5 in block 1 illustrates this type of interaction. Non-crossover interactions are shown by the different slopes of the lines, reflecting a difference in magnitude of the response.

In summary, for each block, the most productive treatments were, generally, T6 and T2, while the least productive were T1, T3 and T5 (Fig. 2A). In general, block 2 was the least productive block, except for treatments T1 and T3 (Fig. 2B).

The number of plants per hectare ranged from 73,800 to 79,800, with CVs of the mean values between 8 and 16%. Finally, the grain density (kg hL^{-1}) ranged from 72.0 to 73.3 with CVs ≤ 2%. The number of plants per hectare and grain density did not vary significantly ($P>0.05$) with blocks and among treatments. However, for both parameters the TxB interaction was significant ($P<0,01$), indicating, again, that treatments influenced those parameters differently under each block and, viceversa, blocks affected those parameters differently under each of the treatments.

Table 7. Grain production, number of plants per hectare and grain density for the different treatments

Treatment	n*	Grain prod.		Plants ha^{-1}		Grain density	
		Mean kg ha^{-1}	CV (%)	Mean	CV (%)	Mean kg hL^{-1}	CV (%)
T1	12	7,198	18.4	76,786	8.3	72.0	2.0
T2	12	9,181	9.4	76,488	8.1	72.7	2.1
T3	12	6,971	19.0	73,810	16	73.0	1.2
T4	12	8,144	12.9	79,464	10	72.2	2.3
T5	12	8,360	21.7	78,571	10	72.8	1.9
T6	12	9,497	15.0	79,762	11	73.3	2.1

* «n» corresponds to the number of surfaces manually harvested to estimate corn production.

Discussion

All the treatments exhibited some degree of soil crusting which, on drying, acquired different com-

Table 8. Analysis of variance: Effects of treatments (T) and blocks (B) on grain production, number of plants per hectare, and grain density

ANOVA Factors	Grain prod.	No. plants ha^{-1}	Grainy density
Treatment (T)	S***	NS	NS
Block (B)	S**	NS	NS
Interaction (T×B)	S***	S***	S**

* «n» corresponds to the number of surfaces manually harvested to estimate corn production.

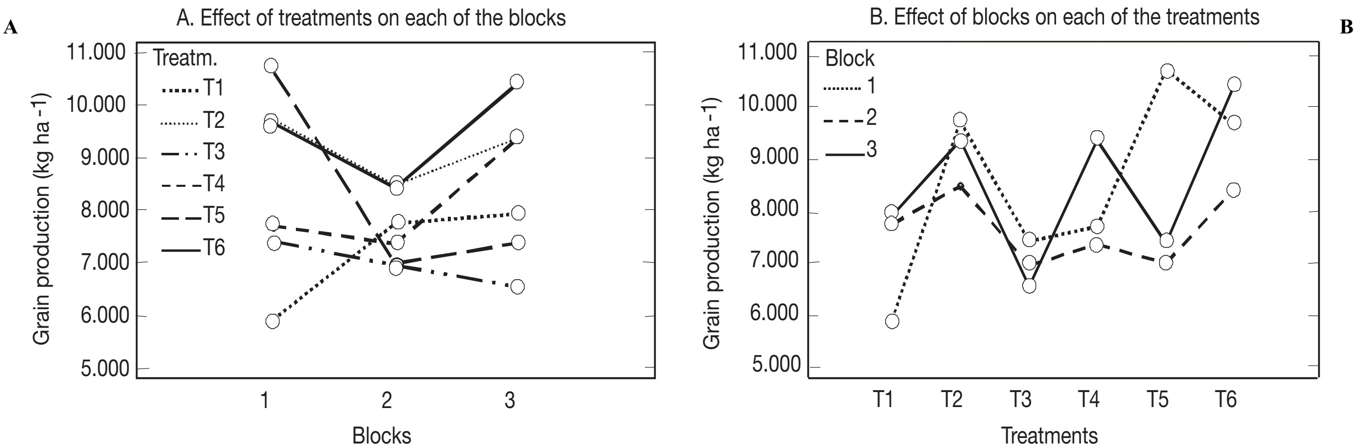

Figure 2. Interaction plots between Treatment x Block (TxB) for grain yield: A. Effect of treatments on each of the blocks; B. Effect of blocks on each of the treatments.

paction (resistance to soil penetration). Since 2 MPa is considered the critical value of mechanical impedance for root growth (Taylor *et al.,* 1966, taken from Levy and Sumner, 1998; Bedard *et al.,* 1997; Sansom *et al.,* 1998; Ringrose-Voase *et al.,* 2000), it was concluded that all treatments exhibited a high to very high surface compaction. As well, all the treatments exhibited some reduction in crop emergence. Seedling emergence and resistance to crust penetration (Rc) were significantly and negatively correlated ($r = -0.91$, $P<0.05$) (Fig. 3), indicating that the most compacted treatments on the basis of Rc were also those presenting the lowest numbers of emerged plants. Thus, for Rc values of almost 6 MPa, the percentage of emerged seedlings was around 60%, whereas for Rc values of around 3 Mpa, the corn emergence was slightly lower than 80%. Several authors have found a negative relationship between surface crust hardness and crop emergence (Helalia and Letey, 1989; Millar, 1988; cited in Sumner, 1993).

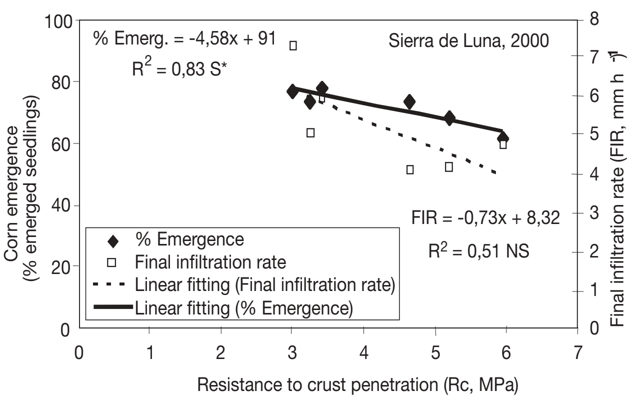

Figure 3. Relationships between corn emergence and soil final infiltration rate with resistance to crust penetration (degree of crusting).

Treatment T6 (application of gypsum after sowing and delayed irrigation until post-emergence) promoted the highest final infiltration rate and exhibited the lowest value of crust penetration resistance (Table 5). Several authors (Sumner and Stewart, 1992; Agassi *et al.,* 1982; Kazman *et al.,* 1983) have shown the beneficial effect of gypsum on soil crusting prevention or reduction. The Ca released from gypsum dissolution increases the salt concentration of the soils above their flocculation value (VF), reducing chemical dispersion of soil colloids. Moreover, gypsum left on top of the soil minimises direct impact of raindrops, and interferes mechanically in crust organisation, preventing the formation of a «layer» that would later form the crust. Nevertheless, it must be mentioned that the addition of gypsum did not completely prevent soil crusting. This was attributed to the following reasons: (i) the applied dose was slightly lower than normal (5 t ha^{-1}), due to a farmer's mistake, and/or (ii) the low dissolution rate of the predominant coarse gypsum particles impeded the immediate positive effect of gypsum when the first rain fell.

Degree of crusting and final infiltration rate were not significantly correlated at $P<0.05$ on the basis of the linear correlation (r) and the Spearman rank correlation (r_s) coefficients. However, the fitting of those parameters to a double reciprocal model was significant at $P<0.057$. This negative relationship suggests that surface crusting might reduce water infiltration into soil. Similar results were reported by Miller and Radcliffe (1992).

Direct drilling on field pea (T4) was significantly ($P<0.05$) more effective than on nearly bare soil (T3) in reducing soil crusting. Legume crops such as field pea act as «green manure», adding organic matter, which, in turn, increases aggregate stability (Mbagwu and Piccolo, 1989). The stable aggregates are more resistant against the destructive forces causing soil crusting. Additionally, the field pea acts as cover crop, protecting the soil surface against the disruptive effects of water drops and wind. Those effects were probably responsible for the greater efficiency of T4 compared to T3 in reducing surface crusting. Roberson *et al.* (1991) indicated that cover crops have rapid and significant effects on macroaggregate stability, even when the total amount of organic C in the soil is apparently not affected. Campbell *et al.* (1993) reported that legume green manure reduced the wind-erodible fraction. Nevertheless, Hill (1990) cited works that indicated that 3 or 4 years are required to ensure the positive effect of no tillage on soil physical properties. Moreover, according to Bandell (1983, 1984) (cited in Hill, 1990), 3 to 6 years are generally required for the yields of no-till corn to equal the yields of corn grown under conventional tillage on the same soil. In this sense, it is worthy to note that direct drilling over legumes (T4) had an intermediate production compared to that of the other treatments, whereas direct drilling on nearly bare soil (T3) was one of the least productive treatments.

As conclusions, none of the treatments applied completely prevented crust development. The application of gypsum to plots with irrigation delayed until post-emergence (T6) was the most effective treatment in reducing soil crusting and enhancing water infiltration into soil. Treatments T2 and T6 were the most effective in enhancing crop emergence and production. The «aguacivera» treatments (T1 and T5), and particularly T1 (control) were the ones inducing the highest degree of crusting and those reducing crop emergence to the greatest extent. These treatments, together with direct drilling on nearly bare soil (T3), were the least productive. Direct drilling treatments followed, in general, an intermediate pattern with respect to the remaining treatments. Direct drilling over pea crop (T4) was more effective than direct drilling over nearly bare soil (T3) in reducing crusting and enhancing emergence and corn production.

The general conclusion of this work is that addition of gypsum to the soil surface and no-tillage or direct drilling are recommended practices to reduce surface crusting, whereas irrigating several times from sowing until emergence («aguacivera») should be avoided (i.e., irrigation should be delayed until post-emergence).

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