Evaluating the effectiveness of a hydrophobic polymer for conserving water and reducing weed infection in a sandy loam soil

J.E. Fernández\textsuperscript{a,*}, F. Moreno\textsuperscript{a}, J.M. Murillo\textsuperscript{a}, M.V. Cuevas\textsuperscript{a}, F. Kohler\textsuperscript{b}

\textsuperscript{a}Instituto de Recursos Naturales y Agrobiología, CSIC, Apartado 1052, 41080 Sevilla, Spain
\textsuperscript{b}Guilford Development, S.A., 109 chemin du Pont-du-Centenaire, 1228 Plan-les-Ouates, Switzerland

Accepted 26 March 2001

Abstract

In this work we tested the influence of different solutions of a hydrophobic polymer named Guilspar\textsuperscript{★}, applied to the soil surface to reduce soil evaporation, on the soil water status, soil temperature, crop performance and weed emergence. Two tests were carried out on a farm of the Guadalquivir river valley, southwest Spain, one with a maize crop and the other with bare soil. In the test with maize, we evaluated the effect of applying a solution of 2% w/v of Guilspar\textsuperscript{★} in water, at the rate of 3.1 m\textsuperscript{-2}, on the crop performance and weed emergence. On both the treated and the untreated control plots, three rates of irrigation were applied, namely 100, 75 and 50% of the locally determined optimal irrigation depth to cover the crop needs for an optimum development and yield. For the case of 50% of the irrigation dose, the performance of the crop treated with the polymer (T50) was much better than that of the untreated control plot (C50). The crop height and green leaf area index for T50 were nearly as good as for the C100 control plants receiving 100% of the irrigation dose. The T50 crop was 73% of the yield of the treated and fully irrigated T100 crop, while the C50 yield was only 38% of the C100 yield. The treated crop reached the different phenological stages quicker than the untreated crop. The polymer was effective in reducing weed emergence. In the test with bare soil, 0.8% v/v of Guilspar\textsuperscript{★} in water, at the rate of 1.1 m\textsuperscript{-2}, kept levels of water content in the soil as high as other solutions with greater amounts both of polymer and water. The average soil water content during the irrigation period in this lower treatment was 34 and 53% higher at depths of 0.15 and 0.25 m, respectively, than in the untreated plots. No influence of the polymer on soil temperature was observed. Results from additional measurements on weed emergence and hydraulic conductivity of the soil surface showed that the polymer was still effective 7 months after application. In fact, the hydraulic conductivity in the range near saturation was 44%
Efficient water use in agriculture is a priority in arid and semiarid zones where water for irrigation is scarce. Improvements in the design of the irrigation systems and in the calculation of the crop water requirements have led to significant reductions in water losses by drainage and runoff. In fruit tree orchards and in other crops where a localised irrigation system can be used, the small area of soil surface wetted by the emitters accounts for a significant reduction of the water lost by soil evaporation ($E_s$, mm). In most cases, however, the whole soil surface is wetted by irrigation. Water losses by $E_a$ are then high, even when the crop canopy is fully developed. In experiments with maize, cotton and sunflower carried out at Cordoba, in an area at about 140 km from the experimental farm used in this study, $E_s$ varied from 80% of reference evapotranspiration ($ET_r$, mm) at 0.8 leaf area index (LAI) to 15% when LAI increased to 4.0 (Villalobos and Fereres, 1990). On our experimental farm, the value of $E_s$ for a mature maize crop (LAI = 3.4) amounted to 18–20% of the crop evapotranspiration ($ET_c$, mm). Measurements were carried out between two furrow irrigations 1 week apart (Fernández et al., 1996).

Efforts to reduce $E_s$ have been made with variable results from the beginning of the agriculture as a rational practice. Tillage and mulching have been traditionally used with that purpose with excellent results (Jalota and Prihar, 1998). Since the 1950s, synthetic products of different natures have also been used with success. Apart from covering the soil with sheets of plastic of different characteristics, synthetic compounds such as bitumen (Sojka and Lentz, 1994) and water absorbing gels (Al-Omran et al., 1991) have been proved to be efficient in reducing $E_s$. Hillel (1980) explains the fundamentals of the reduction in $E_s$ for soils where the surface has been treated with a hydrophobic agent. It is in this context that Guilford Development, S.A. recently registered its silicone polymer, named Guilspar® in Switzerland. The nature of Guilspar® and how it works when applied to soils are described in detail by Cookson (2001a,b). Briefly, when applied to the soil surface as a stabilised potassium salt of silicone, Guilspar® polymerises producing a polysiloxane that undergoes a further condensation reaction with hydroxyl groups on the surface of soil particles. This confers hydrophobicity to the affected layer of soil. The effect of the Guilspar® solution depends on the concentration and rate of application, i.e. depth of penetration. Cookson (2001a) made laboratory studies with bare soil to see the effect of different concentrations and application rates of Guilspar® on $E_s$. He found good results for a solution of 600 kg of polymer in 30,000 l of water per hectare. This is 447 l of polymer, since its density is 1.34. Further studies to evaluate the effect of two different Guilspar® solutions on an aubergine crop were made in a commercial farm, near Barka, in an arid region of the Sultanate of Oman (Cookson, 2001b). The solutions studied contained 100 kg of polymer in 10,000 l of water per hectare, and 300 kg of polymer in 30,000 l of water per hectare. Insufficient replication
and differences on fertiliser applications made it difficult to interpret the results. In other experiments made with okra at the Agricultural Experiment Station of Sultan Qaboos University, Sultanate of Oman, a positive effect of the treatment with Guilspar® on crop yield was found, though this time the tested solutions had large amounts both of polymer and water, 400 and 800 kg of Guilspar® in 40,000 l of water per hectare (Cookson et al., 1999).

The aims of this work were (i) to evaluate the effect of applying a solution of 2% v/v of Guilspar® in water, at the rate of 3 l m⁻², on a maize crop grown under the conditions of the Guadalquivir river valley, southwest Spain; the crop performance and weed emergence were monitored both in treated and untreated plots, irrigated at three different rates, (ii) to find out the effect of Guilspar® solutions with lower amounts both of water and polymer on the soil water content and soil temperature of bare soil plots, in order to determine the optimum application rate, and (iii) to test the efficiency of Guilspar® on controlling the emergence of airborne weeds infesting the field after polymer application. The efficiency of the product was evaluated for a period of up to 7 months after application.

2. Materials and methods

2.1. Experimental site

The work was carried out at the experimental farm La Hampa, of the Instituto de Recursos Naturales y Agrobiología, at Coria del Río near Seville in Spain (37°17'N, 6°3'W, elevation 30 m). The climate in the area is typically Mediterranean, with a mild rainy season from October to April, with 494 mm mean annual rainfall for the period 1971–1999, and hot, dry summers. The average reference evapotranspiration (ETₚ, mm), as calculated by the FAO-Penman equation (Doorenbos and Pruitt, 1977), which Mantovani et al. (1991) evaluated as the best for the area, is 1413 mm for the mentioned period. Most of the experiments reported here were made in 1999, an average year in terms of rainfall (485 mm) and evapotranspiration (1467 mm). The soil of the experimental area is a deep sandy loam, classified as Typic xeroschrept. Homogeneous in depth, the textural values of the top 0.5 m are 60.7% coarse sand, 16.8% fine sand, 9.0% silt and 13.1% clay. The organic matter content was 0.88%. For the top 0.2 m, the volumetric soil water content (θ, m³ m⁻³) at field capacity was 0.21 m³ m⁻³, and 0.08 m³ m⁻³ for a soil matric potential (h, MPa) of −1.5 MPa. The bulk density of this top layer was 1.45 Mg m⁻³. The minimum depth of the water table during the experimental period, measured in a piezometer near the experimental plots, was 5.81 m, not interfering with the experiments.

2.2. Test with maize

The aim of this test was to evaluate the effect of a 2% v/v solution of Guilspar® in water, at the rate of 3 l m⁻², on the crop performance and weed emergence in a maize crop. Previous studies showed that a solution with the same application rate but lower
Table 1
Treatments in the test with maize

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Guilspare® concentration (% v/v in water)</th>
<th>Volume of Guilspare® solution (l ha⁻¹)</th>
<th>Irrigation dose (% of optimal ET_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T100</td>
<td>2</td>
<td>30000</td>
<td>100</td>
</tr>
<tr>
<td>T75</td>
<td>2</td>
<td>30000</td>
<td>75</td>
</tr>
<tr>
<td>T50</td>
<td>2</td>
<td>30000</td>
<td>50</td>
</tr>
<tr>
<td>C100</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>C75</td>
<td>0</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>C50</td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
</tbody>
</table>

The letter T identifies treatments where Guilspare® was applied, and the letter C identifies the control treatments where no Guilspare® was applied. The number following these letters refers to the amount of water applied by irrigation relative (in %) to the optimal crop evapotranspiration (ET_c).

amount of Guilspare® was effective (Cookson, 2001a,b). We increased the amount of polymer to evaluate to what point a high protective effect applied to the crop stimulates the crop response. The economic aspect of this high concentration was not considered as it was planned to define the optimum rate in the separate bare soil experiment described in Section 2.3.

2.2.1. Statistical design and measurements

A randomised block design was used for the test. We applied the solution of Guilspare® to plots irrigated with 100, 75 and 50% of the required irrigation dose to meet the crop water needs. Untreated plots irrigated with the same doses were also considered in the design. We therefore had six treatments (Table 1) at four replications per treatment, which gave us 24 plots, grouped in four blocks. Each plot was 7 m × 7 m, enough to avoid any influence of the neighbouring plots in the central area, where the measurements were carried out. The significance of differences among the treatment means was tested by the analysis of variance (one-way ANOVA), using the least significant difference in the comparison of means. The same applies for the test with bare soil.

The following measurements were made weekly in each plot. Crop height (h_c, m) was determined by measuring the average height of three representative plants. Green leaf area (LA, m²) was calculated also for three plants per plot, by using the relationship obtained at La Hampa by Blázquez (1994) for the ‘Prisma’ variety, based on the length and width of the leaves. The phenological stage was monitored following the criterion of Blázquez (1994), who used the widely accepted criterion of Hanway (1963), but adapted to the ‘Prisma’ variety grown in this experiment. The number of weeds in the plots was monitored on 10 and 24 May, 13 July and 5 August. Each time, a 0.2 m × 0.2 m frame was randomly placed on the ground in the lane between two crop rows (see Section 2.2.2), the number of weeds included within the frame was counted, and the species were identified. Yield was determined from the ears collected in the 3 m × 3 m central area of each plot. After harvesting, the ears were dried and weighed, and the kernels were separated from the cobs. We determined, for each plot, the kernel weight and the weight of a thousand kernels. The weights were referred to 14% kernel moisture.
Maximum daily values of stomatal conductance ($g_s$, mm s$^{-1}$) and net photosynthesis ($P_N$, µmol CO$_2$ m$^{-2}$ s$^{-1}$) were monitored twice when the crop was mature. Measurements were made on 23 June and 15 July, two clear-sky days, between 10.00 and 12.00 GMT, when the values of $g_s$ and $P_N$ were about the maximum. Both parameters were measured with a portable photosynthesis system (LI-6400, LICOR, Lincoln, NE, USA), in the central part of the third or fourth leaf from the top of two representative plants of each plot.

Weather variables were measured in an automatic weather station (Lambrecht, Göttingen, Germany) located some 120 m away from the plots. 30 min average of global solar radiation, photosynthetically active radiation, wind speed, rainfall, air temperature, and relative humidity of the air were continuously recorded. These data were used to calculate weekly average values of ET$_c$.

2.2.2. Soil and crop management

Traditional tillage operations in the area were made before sowing, consisting of a cultivator application 0.25 m depth and disc harrowing down to 0.15 m depth. A heavy wood plunk placed after the discs helped to leave the soil surface smooth and levelled. No tillage was carried out in the treated plots afterwards, to avoid mechanical disruption of the topsoil layer where Guilspare® was applied. The control plots were also not tilled to keep the same conditions as in the treated plots. Maize (Zea mays 'Prisma') was sown on 24 April, in rows 0.75 m apart with 0.33 m between sowing locations within the row. Final crop density was about 80,000 plants per hectare.

The T plots (Table 1) were treated with Guilspare® on 26 April. We treated by spraying with a standard machine currently used for applying pesticides in fruit tree orchards, which had a pump powered by the pulling tractor. The Guilspare® solution was pressurised through a PVC pipe with a line of 2.5 mm diameter holes 5 mm apart, placed horizontally at about 0.5 m from the soil surface.

All the plots were irrigated by a subsurface drip irrigation system installed at the beginning of April. Surface irrigation was not advisable due to the hydrophobic character of the treatment. One drip line was buried at about 0.15 m from each crop row, at a depth of about 0.1 m. One pressure compensating emitter was plugged every 0.4 m in the drip lines. The different irrigation doses (Table 1) were achieved by installing emitters of different discharge rate in each plot: 81 h$^{-1}$ for the plots with 100% of the crop water needs, 61 h$^{-1}$ for 75% and 41 h$^{-1}$ for 50%. Irrigation was made once or twice a week, from 24 April to 10 August, and all plots were irrigated simultaneously. Irrigation rates ranged from 26 to 46 mm, depending on the crop requirements. The frequency and dose of irrigation were enough for keeping the fully irrigated treatments (100% irrigation dose) below a water stress threshold low enough for obtaining an optimum crop development and maximum yield. To achieve this, we checked the appearance of water stress symptoms in the crop 3–4 times a week, and we irrigated also according to our experience (Fernández et al., 1996; Moreno et al., 1996). For the T100 and C100 treatments, a total of 730 mm of water were applied for the whole crop season. This amount is greater than the ET$_c$ determined by Fernández et al. (1996) for a maize crop of similar characteristics in La Hampa, which amounted to 625 mm. Two irrigation events, on 20 and 21 May mainly account for the difference. On those days, 90 mm of water were applied to make
the wet bulbs large enough to ensure water reaching the small root system of the young plants. This practice is unnecessary when furrow irrigation is used, as it was the case of Fernández et al. (1996). The rainfall during the crop period was negligible, except for 19 mm recorded on 28 April.

Enough fertilisers were applied to cover the crop nutrient requirements. The doses and application dates were based on the conclusions of Moreno et al. (1996), Murillo et al. (1997) and Fernández et al. (1998), who studied the use of fertilisers in a similar maize crop in La Hampa. Six hundred kg ha\(^{-1}\) of a complex 15–15–15 fertiliser were applied to all the plots before sowing, on 5 April. Additional K, plus enough urea, macro- and micro-elements were applied throughout the crop season by fertigation. Since the fertilisers were injected in the irrigation water, the plants irrigated with different rates received different amounts of fertilisers. We used fertilisation doses high enough to cover the nutrient needs of the less irrigated plants, in order to avoid differences on crop behaviour due to differences on nutrition.

The crop was kept healthy by doing the required phytosanitary treatments. Weed control was conducted both mechanically, in such a way that the soil surface affected by Guilspar® remained unaltered, and by herbicide applications. In both cases, one lane between two crop rows was left untreated in each plot, to be able to evaluate the effect of Guilspar® on weed emergence and growth. On 20 and 21 May we applied Glyphosate directly to the weeds, without wetting the soil surface, to avoid any interaction with the polymer. We used a brush wrapped with a piece of cloth wetted by the herbicide solution; the maize plants, of about 0.2 m high, were covered during the application with metal pots, to avoid the herbicide reaching them. The weeds very close to the maize plants were not affected by the herbicide, since they were covered together with the cropped plants. In addition, new weeds appeared soon after the herbicide treatment. A few days after the herbicide treatment we began eliminating the weeds mechanically, by using a lawnmower and a hedge cutter. This avoided causing any mechanical disruption or contamination by herbicides to the soil surface layer where Guilspar® was applied. We used continuously the hedge cutter and the lawnmower until the end of July. Harvesting was made on 1–2 September. Harvesting was done manually in the central 3 m \(\times\) 3 m area of each plot. The rest of the cropped area was harvested mechanically.

2.3. Test with bare soil

The solution of Guilspar® used in the test with maize described above, despite been proved efficient in former experiments, had the disadvantage of requiring large amounts of both water and polymer. With the bare soil test, we wanted to define the optimum application rate by evaluating the respective soil–water conservation effects of different treatments, varying water and polymer amount per square meter. In addition, we intended to evaluate whether Guilspar® remained efficient several months after application. The test was carried out on bare soil, since we wanted to focus on the capacity of the polymer for minimising water losses by \(E_s\) and we wanted to avoid any loss through transpiration of the plants. In addition, we evaluated in neighbouring plots the capacity of Guilspar® to limit weed emergence of airborne seeds in the field after treatment.
Table 2
Treatments in the test with bare soil

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Guillspare® concentration (%)</th>
<th>Volume of Guillspare® solution (l ha⁻¹)</th>
<th>Volume of Guillspare® (l ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C1V1</td>
<td>0.4</td>
<td>10000</td>
<td>40</td>
</tr>
<tr>
<td>C1V2</td>
<td>0.4</td>
<td>20000</td>
<td>80</td>
</tr>
<tr>
<td>C1V3</td>
<td>0.4</td>
<td>30000</td>
<td>120</td>
</tr>
<tr>
<td>C2V1</td>
<td>0.8</td>
<td>10000</td>
<td>80</td>
</tr>
<tr>
<td>C2V2</td>
<td>0.8</td>
<td>20000</td>
<td>160</td>
</tr>
<tr>
<td>C2V3</td>
<td>0.8</td>
<td>30000</td>
<td>240</td>
</tr>
<tr>
<td>C3V1</td>
<td>1.2</td>
<td>10000</td>
<td>120</td>
</tr>
<tr>
<td>C3V2</td>
<td>1.2</td>
<td>20000</td>
<td>240</td>
</tr>
<tr>
<td>C3V3</td>
<td>1.2</td>
<td>30000</td>
<td>360</td>
</tr>
</tbody>
</table>

2.3.1. Statistical design and measurements

A randomised block design was used for the test. The plots were near the area in which the test with maize was carried out. We had nine different Guillspare® solutions and a control, totalling 10 treatments (Table 2). We had three replications per treatment, totalling 30 plots, grouped in three blocks. Each plot was 4 m × 4 m, enough to avoid any influence from neighbouring plots in the central area, where the measurements were made.

The soil water content in the top soil layer of each plot most influenced by evaporation was monitored by time-domain reflectometry (TDR) using a Tektronix cable tester (model 1502C, Beaverton, OR, USA). The TDR wave guides comprised three parallel stainless steel rods, 2 mm in diameter and 0.15 m long. Three TDR probes were horizontally inserted into the soil in the centre of each plot, at 0.05, 0.15 and 0.25 m depth. The probes were inserted and tested at the beginning of July, before applying the Guillspare®. TDR measurements were made 2–3 times a week during the irrigation period, and once every 15–20 days during the rainy period (Table 3).

Table 3
Water supplied to the experimental plots in the test with bare soil, from July 1999 to the end of February 2000

<table>
<thead>
<tr>
<th>Date</th>
<th>Water supplied (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irrigation</td>
</tr>
<tr>
<td>20 July</td>
<td>101</td>
</tr>
<tr>
<td>12 August</td>
<td>73</td>
</tr>
<tr>
<td>6 September</td>
<td>68</td>
</tr>
<tr>
<td>19 September</td>
<td></td>
</tr>
<tr>
<td>6 October</td>
<td></td>
</tr>
<tr>
<td>11–12 October</td>
<td></td>
</tr>
<tr>
<td>18–25 October</td>
<td></td>
</tr>
<tr>
<td>29 October</td>
<td></td>
</tr>
<tr>
<td>3–4 December</td>
<td></td>
</tr>
<tr>
<td>12–14 December</td>
<td></td>
</tr>
<tr>
<td>13–16 January</td>
<td></td>
</tr>
<tr>
<td>26 January</td>
<td></td>
</tr>
</tbody>
</table>
Soil temperature \( (T_s, ^\circ C) \) was measured in the centre of each plot at depths of 0.01, 0.05, 0.10 and 0.20 m, by using a digital soil thermometer with a thermocouple probe (Equinise S.A., Seville, Spain). Measurements were made once or twice a week during the irrigation period, and every 15–20 days during the rainy period.

On 22 February 2000, the hydraulic conductivity \( (K, \text{ mm s}^{-1}) \) in the range near saturation was measured in the central area of the Control, C2V1 and C3V3 plots using a tension disc infiltrometer (Perroux and White, 1988). During this period of about 7 months since the application of Guilspar®, rainfall amounted to 421.5 mm (Table 3). The C2V1 plots were chosen because by that time we had the results showing that this was the best of the six treatments. After this set of measurements was finished, we then performed the following test to evaluate the effect of Guilspar® on \( K \) just after application. Next to the area where the test with bare soil was carried out, we repeated the treatments Control, C2V1 and C3V3. The 2 days after application, we measured \( K \) using the tension disc infiltrometer, with three replications of the measurements for each treatment.

2.3.2. Soil management

At the end of May 1999 the soil was tilled as in the test with maize. No further tillage was made. A subsurface irrigation system was installed in the whole experimental area, consisting on a plastic lateral every 0.75 m, with one 11 l h\(^{-1}\) emitter every 0.2 m. The laterals were buried at a depth of about 0.1 m. We found that an irrigation of about 70 mm was enough to wet the soil surface of the experimental area, and to achieve field capacity at least in the top 0.3 m of soil, which was the explored area. The installation and testing of the irrigation system finished at the end of June. The Guilspar® solutions were applied to the plots on 22–23 July. This time we used a watering can for spraying the solutions on the soil surface.

To study the behaviour of Guilspar® under different soil water conditions, we irrigated three times during the dry season, leaving the soil to dry for about 20–25 days between the irrigation events (Table 3). The dry season ended on 19 September, with a rainfall of 70 mm. The plots were kept free of weeds during the whole experimental period, by applications of Glyphosate.

2.3.3. Additional experiment for weed emergence

In an area near the plots used in the test with bare soil, where the soil was highly uniform, we carried out a simple test to assess the efficiency of Guilspar® in controlling weed emergence. As mentioned before, we aimed to evaluate the efficiency of the polymer on controlling infestation of airborne seeds landing on the field surface after Guilspar® application. The emergence of weeds already in the soil as established propagation organs was not tested and can only be reduced to a very limited extent by Guilspar®. We tested two Guilspar® concentrations, less concentrated than the solution used in the test with maize, versus a untreated control (Table 4). We had two replications per treatment, in two groups of three 4 m × 2 m plots. Soil preparation and irrigation management were done as in the test with bare soil. Herbicide treatments (Glyphosate) were carried out until the beginning of August, with the aim of limiting the emergence of weeds whose propagation organs or seeds were in the field before the
application of Guilspar®. The polymer was applied on 5 August, by using a watering can, as in the test with bare soil. The number of weeds appearing on each plot was counted every 15–20 days, until the end of December.

3. Results

3.1. Test with maize

The evolution of \( h_c \) for the different treatments is shown in Fig. 1. The figure depicts the crop response for each treatment as compared with the untreated and fully irrigated C100 crop. In the treated plots with 25% irrigation reduction — the T75 treatment — the crop reached a similar height to the reference C100 crop (Fig. 1b). Without Guilspar®, the height of the C75 crop at the end of the growing period was significantly lower than that of the C100 crop (Fig. 1d). Differences between the T and the C crop were greater for the 50% irrigation reduction. While the height of the T50 crop was similar to that of the C100 crop (Fig. 1c), the C50 crop remained lower than the C100 crop from early in the season (Fig. 1e), clearly showing the effect of the water stress. The evolution of the phenological stage showed that, in general, the crop developed quicker in the T plots than in the C ones, for all the irrigation doses. For instance, in all the plots treated with Guilspar® the seventh leaf appeared on the 37th day after sowing, while in all the untreated plots this happened on the 41st day after sowing. Tasseling happened 1 or 2 days earlier in the treated plots than in the untreated ones, for all the irrigation doses.

The results on the evolution of LA are shown in Fig. 2. Both for the T75 and C75 crops no differences on LA were observed with the reference C100 crop, for most of the crop season (Figs. 2b and d). At the beginning of the senescence period, however, about 25 days before harvesting, both the T75 and C75 crops dried up quicker than the C100 crop. Similar results were obtained for the T50 crop (Fig. 2c). The C50 crop, however, showed a significant reduction in LA, as compared to that of the C100 crop, from the beginning of the growing season (Fig. 2e). In addition, a drastic reduction of LA began in the C50 crop about 1 month after anthesis, while in the C100 crop the quick drying of the leaves at the start of the senescence period did not began until about 40 days after anthesis. Figs. 1a and 2a show no differences, neither on \( h_c \) nor on LA between the T100 and the C100 treatments, indicating that the presence of Guilspar® in a crop irrigated with enough water to cover the crop water requirements did not cause any negative effect due to hypoxia on its development.
Fig. 1. Seasonal evolution of the crop height measured in the experimental plots of the test with maize. Each point represents the average of nine values per treatment. Vertical bars indicate the standard error. Sowing date: 24 April. See Table 1 for the meaning of the treatments.

On 23 June, apart from the difference in $g_s$ between the C100 and T100 crops, the only difference between treatments of the same irrigation regime shown by the ANOVA analysis concerned the C50 crop, which showed an average $g_s$ value significantly lower than that of the T50 crop (Table 5). On 15 July, the only significant difference found was between the T50 and the C50 crops. The $g_s$ values measured in the C50 plants were very low, probably due to the lack of water in the soil. The values of $g_s$ of the T50 plants were greater, despite having been irrigated with the same water amounts and frequency. Differences on $P_N$ between treatments of the same irrigation regime were not significant,
Fig. 2. Seasonal evolution of the green leaf area measured in the experimental plots of the test with maize. Each point represents the average of nine values per treatment. Vertical bars indicate the standard error. Sowing date: 24 April. See Table 1 for the meaning of the treatments.

except for the T50 and C50 crops on 15 July. On that day, the C50 plants showed very little activity in fixing CO₂ from the atmosphere, while the T50 plants still maintained a high photosynthetic activity. It is clear that, for the treatment of 50% reduction on irrigation, the positive effect of Guispare® on the soil water regime, improved the physiological behaviour of the maize plants.

Greater yields were recorded in the T plots than in the C plots, for all the irrigation regimes, although a significant difference within the same irrigation dose was only observed for the T50 and C50 crops (Fig. 3). In fact, the T50 crop gave similar yield
Table 5
Stomatal conductance ($g_s$, mm s$^{-1}$) and net photosynthesis ($P_N$, μmol CO$_2$ m$^{-2}$ s$^{-1}$) measured on 23 June and 15 July in the test with maize (days 60 and 82 after sowing, respectively)$^a$

| Treatment | 23 June | | 15 July | |
|-----------|---------| |---------|----|
|           | $g_s$   | $P_N$ | $g_s$   | $P_N$ |
| T100      | 0.42 ± 0.03 | 41.2 ± 1.9 | 0.34 ± 0.06 | 40.3 ± 5.9 |
| T75       | 0.44 ± 0.03 | 45.0 ± 1.2 | 0.25 ± 0.04 | 33.6 ± 3.8 |
| T50       | 0.47 ± 0.04 | 45.5 ± 2.5 | 0.25 ± 0.13 | 27.2 ± 9.2 |
| C100      | 0.52 ± 0.03 | 43.2 ± 2.6 | 0.31 ± 0.05 | 38.6 ± 3.9 |
| C75       | 0.48 ± 0.04 | 44.7 ± 0.8' | 0.28 ± 0.04 | 40.6 ± 3.7 |
| C50       | 0.37 ± 0.01 | 40.8 ± 0.7 | 0.03 ± 0.0005 | 4.5 ± 1.7 |

$^a$The measurements were made in the central hours of the day when the values of $g_s$ and $P_N$ were about the maximum. See text for further details. The data are mean values of six measurements ± S.E.

(7210 kg ha$^{-1}$) to the T75 crop (6675 kg ha$^{-1}$), while the yield in the C50 crop was substantially lower (3282 kg ha$^{-1}$). The same trend was shown by the average values of ear weight (Table 6). The weight decreased when the irrigation dose was reduced, except in the case of the T50 crop, which gave ears of a similar weight to the T75

Fig. 3. Yield of the treatments studied in the test with maize, for 14% humidity in the kernels. Each bar represents the average of three values. The error bars indicate the standard error. The treatments are explained in Table 1.
crop. The weight of the ears of the C50 crop was significantly lower than that of the T50 crop. Concerning the kernel weight (Table 6), the maximum value was obtained in the T100 crop, though the difference with the C100 crop was not significant. The T75, C75 and T50 crops had similar means, significantly higher than that of the treatment C50.

The number of weeds was always greater in the untreated plots than in the plots with Gispare®, for all the irrigation regimes (Fig. 4). The differences were greater at the beginning of the crop season (10 and 24 May in the figure). Later (13 July and 5 August in the figure) the number of weeds decreased due to the weed control operations carried out during the crop season. These results show a clear effect of Gispare® on preventing weed infection in post-emergence. It has to be taken into account, however, that the number of weeds in the T plots was still too high for an optimum crop development. This could be due to a high number of seeds and other propagation organs already present in the soil before applying Gispare®, whose development was favoured by the water and fertiliser supplies applied throughout the crop season. Most of the weeds present in the plots at the beginning of the crop season had wide leaves. About 90% of the weed population recorded on 10 May were Portulaca oleracea and Amaranthus retroflexus. At the end of the crop season more than the 50% of the weeds belonged to the group of narrow leaf species, with Setaria glauca the most abundant, totalling 35% of the population on 5 July. This was a consequence of the herbicide treatments being more successful in killing the wide leaf species than the narrow leaf ones. The weed infection led us to consider only three replications in the ANOVA analysis of all the studied variables, leaving aside the data of one of the replications (plots) per treatment, the one most affected by the weed infection.

3.2. Test with bare soil

Greater θ values were generally registered in the T plots than in the C plots. Even the C1V1 solution, the one with the lowest amount both of Gispare® and water, proved to be effective in keeping greater humidity levels in the soil. With the same amount of water and double amount of polymer, the treatment C2V1 showed to be the most interesting, since the results obtained in this treatment (Fig. 5) were as good as those of other
Fig. 4. Number of weeds in the experimental plots of the test with maize, at different dates of the cropping season. Each bar represents the average of three values. The error bars indicate the standard error. The treatments are explained in Table 1. Sowing date: 24 April.
Fig. 5. Volumetric soil water content measured by TDR at the three explored depths, in the plots of the Control and C2V1 treatments, during the test with bare soil. Each point represents the average of three values. Vertical bars indicate the standard error. The arrows represent the three irrigation events (Table 3). The treatments are explained in Table 2.
treatments with greater amounts of both water and Guilspare® (data not shown). For the irrigation period, from day of year (DOY) 201–264, despite the fact that no differences in \( \theta \) were found at 0.05 m depth between the Control and the C2V1 plots (0.13 m\(^3\) m\(^{-3}\) in each case), the average \( \theta \) values at 0.15 m were 0.13 m\(^3\) m\(^{-3}\) for the Control plots and 0.16 m\(^3\) m\(^{-3}\) in the C2V1 plots, and at 0.25 m these values were 0.13 and 0.19 m\(^3\) m\(^{-3}\), respectively. The results were consistent for the three irrigation and drying cycles carried out from July 20 (DOY 201) to the first rainfall event on September 19 (DOY 262). For all treatments, differences between treated and untreated plots were greater as depth increased. This may be due to the fact that the irrigation pipes were buried at a depth of about 0.1 m and, consequently, the top centimetres of soil were less affected by the water supplied by irrigation than the underlying layers.

The results obtained during the rainy period show that the polymer was still effective in December, about 5 months after being applied. The high soil water contents measured on DOY 298 (Fig. 5), just after 8 rainy days in which 208.9 mm of rainfall were recorded (Table 3), suggest that part of this water infiltrated into the soil despite Guilspare®. Therefore, the different treatments likely caused a high heterogeneity among plots on rainfall infiltration, which certainly affected the results on \( \theta \) at the end of the experimental period.

When recording \( T_s \), the measuring period of each day lasted for about 08.00 to 12.00 GMT. Differences in air temperature greater than 15°C between both hours are usual in our area. To avoid this influencing the results on \( T_s \), we organised the data by comparing the plots of the two or three treatments measured at about the same time of day. Fig. 6 shows the results of the Control plots versus two treatments with increasing amounts of both water and Guilspare®, C2V1 and C2V3. The differences observed between treatments were not significant in most cases. The same situation was observed for the other treatments not shown in the figure. These results are not surprising, taking into account the complexity of the processes involved. As Hanks and Ashcroft (1980) said: "water content also influences heat dissipation in soil through its effect on thermal conductivity, heat capacity, and thermal diffusivity. The result of an increased water content may be to increase or to decrease soil temperature depending on the specific situation".

The measurements with the tension disc infiltrometer 2 days after Guilspare® application show that the hydraulic conductivity of the topsoil layer was greatly reduced by the polymer (Fig. 7a). In fact, the lowest \( K \) values were measured for the C3V3 treatment. This effect still remained, though to a lower extent, 7 months after the application (Fig. 7b), despite the rainfall events of the autumn and winter (Table 3). It is likely that the reduction of \( K \) was due to drier soil surface created by the polymer in the treated plots compare to the untreated soil layer of the Control plots. Although the difference was more marked in the C3V3 treatment, the reduction of \( K \) in the C2V1 treatment was substantial.

3.3. The additional experiment on weed emergence

The number of weeds in the treated plots was always lower than in the untreated control plots, showing that Guilspare® was effective in minimising weed emergence
Fig. 6. Soil temperature measured at the four explored depths, in the plots of the Control, C2V1 and C2V3 treatments, during the test with bare soil. Each point represents a single measurement. The treatments are explained in Table 2 and water supplied events are detailed in Table 3.
Fig. 7. Hydraulic conductivity in the range near saturation, measured in the soil surface of the Control, C2V1 and C3V3 plots 2 days after applying the Guilsparë® solution (a), and on 22 February 2000, 7 months after the polymer application (b). Each point represents the average of three values. Vertical bars indicate the standard error. The treatments are explained in Table 2.
Fig. 8. Seasonal evolution of the number of weeds in the plots of the three treatments of the additional experiment to evaluate the effect of Gulspar® on weed emergence. Each point represents the average of two values. Vertical bars indicate the standard error. The treatments are explained in Table 4. The polymer was applied on day 217 of year.

(Fig. 8). After the first 2 months from the beginning of the experiment on 5 August (DOY 217), the number of weeds per plot was greater in the Control plots than in the T1 and T2 plots, though differences were small due to the little time that had passed after the last herbicide treatment, where all weeds were killed. On 25 October (DOY 298), nearly 3 months after the beginning of the experiment, the differences between the Control and the T1 and T2 plots were remarkable. The last set of measurements on 22 December (DOY 356) showed a greater increase in the number of weeds in the treated plots than in the control ones, indicating perhaps a certain decrease in the efficiency of Gulspar® on weed control. The heavy rains of the autumn (Table 3) may have contributed to this loss in efficiency. Despite that, however, 5 months after applying Gulspar® the differences between the control and the treated plots were still considerable. Although the number of weeds was usually greater in the T2 plots than in the T1 plots, the little differences registered between both treatments indicate that the T1 treatment, with half of the polymer amount of the T2 treatment, was enough for an effective weed control. Some of the weeds were Cypoglossus rotundum, a common species in the area, which has subterranean propagation organs that the contact herbicide used at the beginning of the experiment may not have totally destroyed.
4. Discussion

The results of both the test with maize and the test with bare soil indicate that **Guilspare** is effective in maintaining water in the soil by reducing water losses from evaporation, this having a positive effect on crop development and yield. This is especially noticeable for conditions of severe water stress, 50% irrigation reduction in our case. For the case of 25% reduction on irrigation, the positive effects of **Guilspare** on crop development (Figs. 1 and 2, and results on the evolution of the development stage) and on gas exchange (Table 5) were not great enough to avoid a reduction on yield similar to that recorded in the non treated C75 treatment (Fig. 3). Results on yield, however, should be considered with caution when evaluating the efficiency of **Guilspare** or any other compound influencing soil water status. It is known that, in maize, just a few days of stress during anthesis or grain filling can cause dramatic reductions in yield, although the moisture situation had been favourable for the crop for most of the growing season. Shaw (1988) reported data from different studies showing marked yield reductions of up to 48% due to water stress at the blister-kernel stage. In our case, a clear positive effect of **Guilspare** on yield was found for the case of 50% water restriction (Fig. 3). Thus, the best range of use for **Guilspare** seems to be a crop cultivation under severe water restriction. The results from the bare soil test showed that the polymer was able to keep greater values of θ in the soil (Fig. 5), which can explain the observed improvements on the crop performance. Previous research on soil columns under laboratory conditions showed that **Guilspare** was able to reduce $E_s$ by 84% (Cookson and Kacicov, 1999). Fernández et al. (1996) calculated that the value of $E_{c}$ for a maize crop in the area was about 6250 m$^3$ ha$^{-1}$, and that the value of $E_s$ when the crop was fully mature averaged 18–20% of $E_{c}$ in that development stage. It is reasonable to think of greater values of $E_s$, as compared to $E_{c}$, for the crop periods in which the crop foliage did not fully cover the soil surface. That means that the value of $E_s$ for the whole crop period is greater than 1250 m$^3$ ha$^{-1}$, and a large part of this amount can be saved by using **Guilspare**. In terms of gas exchange, the low values of $g_s$ measured in the C50 treatment on 23 June could be a consequence of the low θ values in the C50 plots. In the same way, the greater values of $g_s$ measured on that day in the T50 plants could be due to greater values of θ due to **Guilspare** effects. On 15 July, the low values of both $g_s$ and $P_N$ measured in the C50 plants showed a low physiological activity caused by the lack of water in the soil. The T50 plants, however, were able to keep high levels of water exchange and CO$_2$ fixation. It seems that, in this treatment of severe water restriction, **Guilspare** was able to delay the physiological death of the crop. We do not have a clear explanation for the results on the evolution of the phenological stage, showing a quicker crop development in the treated plots than in the untreated ones. An increase in $T_s$ due to **Guilspare** could explain these observations. Cookson (2001b) found that $T_s$ was greater in treated than in untreated soils, with differences of 2.5 and 1°C at 0.02 and 0.1 m depth, respectively. However, we found no clear differences in $T_s$ due to the polymer (Fig. 6). The differences in crop development could be also due, at least in part, to the differences in weed infestation (Fig. 4). However, we have no evidence supporting this assumption.

Besides the beneficial effects on water saving and crop performance, **Guilspare** is efficient in reducing weed infection (Figs. 4 and 8). This may be due to the top layer of
the soil becoming hydrophobic after applying the polymer. The seeds arriving on a treated area find a barrier of dry soil where germination is possible but greatly impeded by the lack of water. Whether this or other effects of Guilsparé® are responsible for the reduction on weed emergence, is something that should be analysed in further studies. Our results show, however, that the application of the polymer could minimise the use of herbicides, leading to a reduction on both the costs of producing the crop and the risk for environmental contamination. Regarding the duration of the protection offered by the polymer, Figs. 7 and 8 show that noticeable effects lasted for quite a few months after application, even after the occurrence of a few rainy events (Table 3).

It seems, therefore, that the use of Guilsparé® can have clear advantages in areas of coarse soils where water for agricultural use is scarce. There are some aspects, however, that could restrict the potential use of Guilsparé® by the farmers. First, the amounts both of water and polymer that have been used in the test with maize, and also in the studies made in the past (Cookson, 2001a; Cookson et al., 1999), could be considered as far too big by most farmers. The test with bare soil however determines an optimum for water saving being 0.8% v/v in water, at a rate of 11 m⁻². This amount of water can be still considered as too high by many farmers, not only because of the lack of water in many arid and semiarid areas, but also because applying such a high volume per unit of soil surface is expensive. We agree with the comments by Cookson (2001a) regarding the need for further research on different application methods for Guilsparé®. Further research should focus on the suitability of using other spraying systems allowing for smaller drop sizes. Recent laboratory research by Guilford Development, S.A. in Switzerland has resulted in the development of a new Guilsparé® formulation. This new formulation greatly reduces the amount of both polymer and water needed. Future field tests will concentrate on validating the new formulation, where the outcome appears promising.

Another aspect to consider when evaluating the use of Guilsparé® in commercial agriculture is its role as a barrier against infiltration. Our results show that water can infiltrate on a soil treated with the polymer, but at a reduced infiltration rate (Fig. 7). This conditions the irrigation system, reduces the local caption of the rainfall water, and could increase soil erosion by runoff. These shortfalls can be minimised by treating only the soil surface on the rows where the product is being more profitable for plant growth, leaving strips of untreated soil where water can infiltrate freely.

5. Conclusions

Applying Guilsparé® to the soil increases the soil water content of the top soil layers, probably by reducing hydraulic conductivity within the treated layer to nearly zero, thus leading to a reduction of water loss by evaporation. Under the conditions studied, this had a positive effect on crop development and yield, especially when the restriction of water was severe (50% irrigation reduction). No effect of the polymer on soil temperature was observed, although the crop developed quicker in the treated plots than in the untreated ones. Stomatal conductance and net photosynthesis were greater at the later stages of the crop in the cases where the polymer was applied. The treatment with Guilsparé® reduced
weed emergence. Our results on weed emergence and hydraulic conductivity of the top soil layer shows that the polymer was still working 7 months after application, despite rain events occurring in that period, although we do not know to what extent its efficiency could have decreased. Results from the bare soil experiments indicates that 801 of Guilspare® diluted to 10,000 l in water per hectare (0.08% v/v) may be enough to get optimum water savings. This amount of water may result too high for the polymer to be widely accepted by the farmers. Further studies on other methods of application with reduced application rates are underway. Preliminary laboratory tests have permitted the development of a new formulation, which should undergo a series of validation tests. On the one hand, the use of the polymer in commercial orchards could be curtailed by its capacity to reduce infiltration of water into the soil, especially when surface irrigation technique is used. On the other hand, the capacity of Guilspare® to help gather the water during heavy rainfall could be positively combined with surface or subsurface drip irrigation, to increase the water use efficiency.

Acknowledgements

We are grateful to the staff of La Hampa, for help in the soil preparation and crop management. Thanks are also due to Beatriz Molina, Inmaculada Velázquez, Milagros Alcalá, Luz-Maria Maqueda and José-Luis Zurita, for their help in the experimental work. The manuscript was reviewed by Ian Horman, Scientific Officer, Nestlé Research Centre, Lausanne, Switzerland.

References

Cookson, P., 2001b. Evaluation of hydrophobic polymer application to soil. II. Effect of application rates on soil water conditions under a commercially grown crop. Sultan Qaboos University Journal, in press.


