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By

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Introduction

The soils of the Mediterranean region have an unstable structure and are susceptible to seal formation. Seals drastically reduce the infiltration capacity of the soil. Depending on soil type, up to 50% of the rain may be lost by runoff. In addition, increased runoff enhances soil erosion.

In order to improve water management and reduce soil erosion in these soils under rainfall conditions, the following overall aim and specific objectives were outlined.

Overall aim of the proposal

To study the sealing phenomena in soils from Portugal and Israel and the effect of seals on infiltration, runoff and soil erosion. Methods for stabilizing soil structure, improving rain penetration and preventing runoff and erosion were to be evaluated.

Specific objectives of the proposal

1. To study the effect of soil sodicity and water quality on the hydraulic properties of the soils.
2. To investigate the effect of soil properties on seal formation, infiltration, runoff and soil erosion.
3. To study the effect of rain properties (kinetic energy of drops, rain intensity and erosivity) on sealing, runoff and erosion.

4. To evaluate the effect of slope on soil erosion.

5. To study the effects of soil amendments (polymers and phosphogypsum) on seal formation, runoff and soil erosion.

Research activities

In accordance with the aforementioned objectives the following studies were carried out:

I. In Israel

1. Effect of water quality and amendments on the hydraulic properties and erosion from several mediterranean soils (Appendix 1). The manuscript was published in Soil Technology 4:135-146 (1991). It addressed objectives #1, #2 and #5.

2. Water quality and PAM interactions in reducing surface sealing (Appendix 2). The manuscript was published in Soil Sci. 149:301-307 (1990). It addressed objectives #1 and #5.

3. Water-droplet energy and soil amendments: Effect on infiltration and erosion (Appendix 3). The manuscript was published in Soil Sci. Soc. Am. J. 54:1084-1087 (1990). It addressed objectives #3 and #5.

4. Rain energy and soil amendments effects on infiltration and erosion of three different soil types (Appendix 4). The manuscript was published in Aust. J. Soil Res. 29:455-465 (1991). It addressed objectives #2, #3 and #5.

5. Slope, aspect and phosphogypsum effects on runoff and erosion (Appendix 5). The manuscript was published in Soil Sci. Soc. Am.

J. 54:102-1106 (1990). It addressed objectives #4 and #5.

6. Soil dispersibility, rain properties and slope interaction in rill formation and erosion (Appendix 6). The manuscript was send for publication to Soil Sci. Soc. Am. J. It addressed objectives #2, #3 and #4.

II. In Portugal

1. Rainfall erosivity and the universal soil loss equation (USLE) suitability for Portugal - Field study (Appendix 7). The study addressed objectives #3.

2. Soil amendments and mulch effects on runoff and erosion - laboratory study (Appendix 8). The study addressed objectives #2 and #5.

3. Soil amendments and mulch effects on runoff and erosion under natural rain conditions (Appendix 9). The study addressed objectives #2 and #5.

Appendix 1

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EFFECT OF WATER QUALITY AND AMENDMENTS ON THE HYDRAULIC PROPERTIES AND EROSION FROM SEVERAL MEDITERRANEAN SOILS*

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Abstract

The response of six sandy-loam soils from Portugal and Israel to leaching with sodic and saline water and to simulated rain was studied. The dominant clay mineral in the soils from Portugal was kaolinite, whereas smectite predominates in the soils from Israel. The permeability of the soils depended on the soil texture: it decreased with an increase in the silt and clay content. The response of the soils to sodicity depended on the electrolyte concentration; salt concentrations exceeding 10 $mmol_c \cdot L^{-1}$ was enough to prevent the deleterious effect of exchangeable sodium (≤20%). When leaching with distilled water (simulating rain water), the presence of primary minerals and lime determine the susceptibility of the soils to sodicity. The calcareous loess from Israel was the least susceptibility to sodicity.

The six soils were susceptible to sealing, high runoff and erosion when exposed to rain. The soil surface was particularly vulnerable to sealing due to both the mechanical impact of raindrops and the low concentration of electrolytes in the rainwater. Seal formation was due to two mechanisms:

(i) physical disruption of aggregates at the soil surface which depended on the impact energy of raindrops and the inherent aggregate stability; and

(ii) chemical dispersion which depended on the mineralogy of the clay, the ESP, and the electrolyte concentration.

When the impact of the drops was prevented, or when the anionic polymer was sprayed at the soil surface, physical breakdown of the aggregates was reduced and runoff and erosion were slight. When the electrolyte concentration was high, the chemical dispersion was small and runoff and erosion decreased, compard with the control. The smectite soils from Israel were more susceptible to sealing than the kaolinitic soils from Portugal.

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6

1 Introduction

The permeability of a soil to water depends on soil texture, mineralogy, the exchangeable sodium percentage (ESP) of the soil and the salt concentration of the percolating solution (FRENKEL et al. 1978, SHAINBERG & LETEY 1984). Saturated hydraulic conductivity (HC) decreases with increase in clay plus silt content in the soil and tends to decrease with increasing ESP and decreasing salt concentration, but can be maintained even at high ESP levels provided the electrical conductivity (EC) of the percolating water is above a critical (threshold) level (QUIRK & SCHOFIELD 1955, McNEAL & COLEMAN 1966). Conversely, when low electrolyte concentration water was applied, an ESP value of 5 was enough to cause a two orders of magnitude decrease in the HC of 71 Australian soils (McINTYRE 1979).

Seasonal rainfall is typical of many arid and semi-arid regions where irrigation is practised (SHALHEVET & KAMBUROV 1976). The electrolyte concentration of rain water is very low, and thus the deleterious effect of exchangeable sodium will be more evident during the rainy season than during the irrigation season. Moreover, some irreversible deterioration of the physical properties of the soils may take place at low ESP values during the rainy season and this damage cannot be remedied during the irrigation season.

Most previous studies of the effect of solution concentration and soil ESP on physical and hydraulic properties of soils have been done with solution concentrations exceeding 3 $mmol_c \cdot L^{-1}$ (EC > 30 mS m^{-1}) and on soils with ESP values >10 (US SALINITY LABORATORY STAFF 1954, McNEAL & COLEMAN 1966). One objective of this work was to study the HC response of several Mediterranean soils (from Israel and Portugal) with various clay contents and clay mineralogies, to soil sodicity when leached with distilled water, simulating rain water.

The effect of ESP on the infiltration rate (IR) of soils from Israel was studied by KAZMAN et al. (1983) using distilled rainwater. They found that the IR was much more sensitive than the HC to the ESP of the soil. The higher susceptibility of the soil surface to ESP levels <5 was explained by three factors (KAZMAN et al. 1983, OSTER & SCHROER 1979):

(i) Mechanical impact of raindrops enhances dispersion in soils which have the potential to disperse due to exchangeable sodium;

(ii) absence of sand particles, which slows clay dispersion and clay movement by absorbing the impact energy of raindrops, when present; and

(iii) low electrolyte concentration in the applied distilled water.

At the soil surface the electrolyte concentration will remain low even for soils which release electrolytes into the soil solution, e.g. calcareous soils. It can thus be expected that IR will not be influenced to the same extent by the mineral dissolution rate of a soil, as is the case with HC.

Crust formation is due to two mechanisms, viz. a physical disruption of soil aggregates caused by the impact action of raindrops, and a chemical dispersion which depends on soil ESP and the electrolyte concentration of applied water (AGASSI et al. 1981). In soils with low

ESPs or when electrolytes are present in the applied water, chemical dispersion is prevented. Thus spreading phosphogypsum (PG), a byproduct of the fertilizer industriy, on the surface of soils and prevented clay dispersion and maintain high IR (KAZMAN et al. 1983).

Another way of reducing seal formation and maintaining high IR is by improving soil structure and aggregate stability at the soil surface. The use of organic polymers (polyacrylamids and polysaccharides) for improving soil structure and soil permeability has recently been studied (BEN HUR et al. 1989, SHAINBERG et al. 1990). The combined application of anionic polyacrylamide (PAM) with electrolytes had a more pronounced effect than the effect of either of the two alone in improving infiltration (SHAINBERG et al. 1990, SMITH et al. 1990). The current interest in PAM is enhanced by its low price (\$3 kg^{-1}) and low application rate (20 kg ha^{-1}), which makes its possible use in agriculture economically viable. The low application rate of PAM followed our understanding of the role of seal formation in determining the IR and hence the realization that only the soil surface needs to be treated, rather than mixing the polymer with the entire cultivated layer.

The objectives of this study were

(i) to evaluate the effect of clay content and mineralogy on the HC response of sodic soils from the Mediterranean region to leaching with distilled water (simulating rain water);

(ii) determine the effect of the soil properties on the IR of Mediterranean soils exposed to simulated rain; and

(iii) study the effect of amendments (PG, PAM) on the IR, runoff and erosion of these soils.

2 Materials and methods

Six sandy soils were collected in Portugal and Israel from regions with winter precipitation exceeding 350 mm. A few of their physical and chemical properties are presented in tab. 1. Whereas the soils from Israel are young soils derived from aeolian dust, the Portuguese soils are old and were derived from shist rocks and river deposits. Thus the dominant clay mineral in the Portuguese soil was kaolinite mixed with illite or smectite in low percentages, and the dominant clay mineral in the Israeli soils was smectite mixed with illite (loess) or kaolinite (hamra). Similarly, the pH of the Portuguese soils was slightly acidic (<7.0), whereas that of the Israeli soils exceeded pH 7.0. The ESP of the six soils was low (<3.0).

3 Hydraulic conductivity studies

Soil columns were prepared by packing 100 g of soil into plastic cylinders 50 mm in diameter to a bulk density of 1.25 to 1.45 g cm^{-1} (PUPISKY & SHAINBERG 1979). The columns were initially wetted from the bottom and kept saturated. A filter paper was placed on the soil surface to avoid disturbance when solutions were applied or removed from the soil column. To eliminate the effect of flow rate the initial rate of flow in all soils columns was maintained at similar values by adjusting the hydraulic heads. The ESP of the soils in individual columns was adjusted to desired levels (ESPs about 5, 10 or 20) by leaching with 0.5 M $NaCl$-$CaCl_2$ solutions of a corre-

Country	Soil	International Classification	Sand Coarse %	Sand Fine %	Silt %	Clay %	CEC $cmol_c$ kg^{-1}	O.M. %	pH	Exchangeable Ion Percent K^+	Mg^{++}	Na^+	Clay Mineralogy
Portugal	Mitra-Pg	Lithic Xerochrepts	44.0	35.5	13.3	7.2	3.9	1.6	5.2	7.4	5.1	2.0	K(5), Q(2), I(1)*
	Vale Formoso, V_x	Lithic Rhodoxeralf	31.0	28.2	29.2	11.8	9.0	1.3	5.8	5.1	27.5	1.5	K(5), Q(1), S(2)
	Alvalade, AL	Typic Xerofluvent	5.6	43.6	34.0	16.8	10.7	1.9	6.3	1.0	46.3	1.7	K(5), Q(2), I(2)
Israel	Hamra (8% clay)	Typic Rhodoxeralf	85.0		7.0	8.0	6.3	0.5	7.4	1.0		1.5	S(5), K(3)
	Hamra (18% clay)	Typic Rhodoxeralf	74.0		8.0	18.0	11.7		7.2			2.2	S(5), K(3)
	Loess	Calcic Haploxeralf	44.0		38.0	18.0	15.7	0.8	7.9			2.8	S(5), I(2)

* K = Kaolinite, Q = Quartz, I = Illite, S = Smectite
1 = weak ... 5 = strong relative peak intensities of each mineral on the diffractogram

Tab. 1: *Some physical, chemical and mineralogical properties of the soils used.*

Soil	Bulk density $g \cdot cm^{-3}$	Pore volume mL	"Base" HC $mm \cdot h^{-1}$	Relative HC (%) in salt solutions SAR 10 0.05 M	SAR 10 0.01 M	SAR 20 0.05 M	SAR 20 0.01 M	Effluent properties at 200 ml of distilled water SAR 10 pH	SAR 10 EC $dS \cdot m^{-1}$	SAR 20 pH	SAR 20 EC $dS \cdot m^{-1}$
Mitra — PG	1.45	31.3	5.8	1.00	0.88	1.00	0.80	6.6	0.04	6.7	0.08
Vale Formoso, V_x	1.25	42.0	3.3	1.00	1.00	1.00	0.87	7.2	0.07	7.3	0.08
Alvalade, AL	1.25	42.0	3.2	0.95	0.85	0.92	0.76	7.2	0.07	7.2	0.15
Hamra 8%	1.3	39.0	180	1.00	1.00	0.98	0.82	7.8	0.04	—	—
Hamra 18%	1.25	42.0	93	1.00	0.93	0.80	0.50	—	—	—	—
Loess	1.25	42.0	9.0	1.00	0.85	0.84	0.60	—	0.15	—	0.26

Tab. 2: *Physical and chemical properties of the soil columns in the hydraulic conductivity (HC) measurements.*

sponding sodium adsorption ratio (SAR) value. The HC of each soil column obtained with the 0.5 mol$_c$·L^{-1} solution (where the EC is high enough to eliminate ESP induced HC differences) was taken as the 'base' value (tab. 2). Subsequently, the individual columns were leached with solutions of the same SAR but of successively decreasing salt concentrations (0.05 M and 0.01 M) until steady state conditions for HC and EC were attained. Finally the columns were leached with distilled water. Clay concentration in the effluent of the distilled water leachate was determined gravimetrically. In addition pH and EC were measured.

4 Infiltration studies

Soil samples for IR experiments (<4 mm) were packed in 300×500 mm perforated trays, 20 mm deep, over a layer of coarse sand. The trays were placed in a rainfall simulator (MORIN et al. 1967) at a slope of 5% and subjected to either mist or rain with impact energy. The rain intensity was 35 mm h^{-1}. Distilled water was used to simulate rainwater but, owing to dust in the rain simulator room, the actual EC of the water was 5 mS m^{-1}. Typical mechanical parameters of the simulated rain were: median raindrop diameter of 1.9 mm; median drop velocity of 6.02 m s^{-1} and total kinetic energy of 805 J m^{-2}h^{-1} (= 23 J·m^{-2}· mm^{-1}). The runoff water and the effluent volumes were measured, and the infiltration rate was calculated.

In another series of experiments, powdered phosphogypsum was spread on the soil surface at a rate of 5 t h^{-1}. In the PAM treatments 4 mm of polyacrylamide (PAM) solutions with concentrations of 500 ppm were sprayed at the soil surface and allowed to dry. The amount of PAM applied was equivalent to 20 kg ha^{-1}. PG at the rate of 5 t h^{-1} was spread at the PAM treated soil surface prior to the rain application.

5 Results and discussion

5.1 Hydraulic conductivity

The base HC values of the soils using 0.5 M solutions of SAR 10 and 20, the relative HC of the soils in solutions of 0.05 M and 0.01 M at the same SAR values together with the pH and EC of the distilled water effluent (at an effluent volume of 200 cm^3) are presented in tab. 2. It is noted that the soils containing high percentage of fine sand plus silt have low 'base' HC levels (<10 mm h^{-1}). The sandy loam soils from Israel have exceptionally high 'base' HC values due to the high percentage of coarse sand.

Replacing the 0.5 M solutions of SAR 10 with 0.05 M solutions of the same SAR had a minimal effect on the HC of the soils (tab. 2), indicating that this concentration is enough to prevent the deleterious effect of ESP 10. When the 0.5 M solutions of SAR 20 were replaced with 0.05 M solutions of the same SAR, a slight decrease in 'base' HC was observed (tab. 2). This decrease was related to the clay content of the soils — as the clay content increased the decrease in relative HC was more pronounced. When the 0.05 M solutions of SAR 10 and 20 were replaced with 0.01 M solutions, a more pronounced drop in relative HC was observed, and the drop increased with both the increase in the ESP and increase in clay content of the soils. The dominant mechanism which accounts for the decrease in HC of soils in equilibrium with >0.01 M solution is swelling

10

(SHAINBERG & LETEY 1984). Thus, only soils with high contents of expansive clays (smectites) showed a significant decline in HC (tab. 2). Swelling of clays in soils increased with increasing ESP and decreasing electrolyte concentration and, as a result, the size of pores which conduct flow decreased and the HC diminished. The decrease in HC of the Israel soils is more pronounced than that of the Portuguese soils (with similar clay content), because smectites predominate in the clay fraction of the Israeli soils (tab. 1).

The relative HC's of the six soils, when the 0.1 M solutions were replaced with distilled water (DW) are shown in fig. 1. The response of the soils varied considerably. Whereas the HC of the two noncalcareous soils from Israel dropped sharply to zero, at both ESP levels, the HC of the noncalcareous soils from Portugal decreased more gradually (fig. 1). The change in HC of the silty loam loess from Israel was least affected by the leaching with DW (fig. 1). Even when saturated with ESP 40, the relative HC of the loess was maintained at 17% (fig. 1). The insensitivity of the sodic loess to leaching with DW was, in spite of the high content of silt, a size fraction which is considered to weaken the structure of the soil.

The different response of the six sodic soils to the leaching with DW (simulating rainwater) may be explained as follows: The HC of soils with low sodicity (ESP ≤ 20) is very sensitive to the electrolyte concentrations in the soil solution at the low range of concentrations <0.03 M (SHAINBERG et al. 1981a). When the electrolyte concentration is below the flocculation value of the clay, the clay disperses, moves, and blocks the conducting pores and seals the soil. When the electrolyte concentration exceeds the flocculation value of the clay, dispersion is prevented and swelling becomes the dominant mechanism causing HC decline (SHAINBERG & LETEY 1984). As the flocculation value of smectites with ESP≤ 20 is below 0.003 M (OSTER et al. 1980), this concentration is enough to diminish clay dispersion and a significant decrease in HC. The EC of DW effluent of the loess soil, at 200 cc (about 5 pore volumes) were 0.15, 0.26 and 0.29 $dS \cdot m^{-1}$ for ESP values of 10, 20 and 40 respectively (tab. 2 and fig. 1). These EC values, which result from the dissolution of lime, prevent clay dispersion and clogging of the conducting pores. Increase in the ESP of the soil increased the EC of the effluent because exchangeable Na serves as a sink for dissolved Ca.

The hamra soils from the coastal plain of Israel represent the other extreme. These soils are from a region with an annual rainfall of 600 mm. The texture of the soil is sandy and the permeability is high. Thus efficient leaching took place during the rainy seasons and the soils do not contain unstable minerals. In the column experiments, when these soils were leached with DW, the EC of the effluent dropped to 0.04 $dS\ m^{-1}$ which is equivalent to electrolyte concentration of 0.4 $mmol_c \cdot L^{-1}$. This concentration is below the flocculation value of clays with ESP 10 and 20 and the clays disperse and block the conducting pores.

The Protuguese soils are intermediate in their response to sodic conditions (fig. 1 and tab. 2). The Mitra soil is the most susceptible of the three soils to sodic conditions, and the Vale Formoso soil is the most stable one. The EC of the DW effluent was 0.04 and 0.07 $dS \cdot m^{-1}$ for the Mitra and Vale Formoso soils, respectively. Leaching by winter rain of

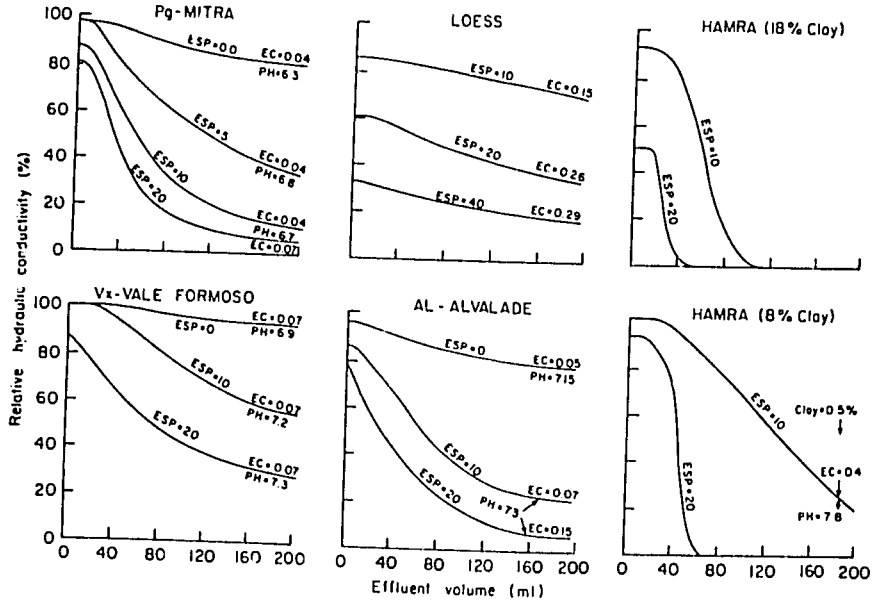

Fig. 1: *The relative hydraulic conductivity of the six soils as function of effluent volume when the 0.1 M solutions are displaced by distilled water.*

the Mitra soil was more efficient than leaching of the Vale Formoso soil because of a low percentage of silt and clay in the final soil. The Alvalade soil being an alluvial soil was more susceptible to sodicity than the kaolinitic Vale Formoso soil, in spite of the presence of primary minerals which dissolve readily (the EC of the effluent of ESP soil was 0.17 $dS \cdot m^{-1}$).

5.2 Infiltration rate

The IR of the two soils from Israel, as a function of cumulative rain, is presented in fig. 2 and tab. 3. Four treatments were applied: control, rain without impact energy (mist), treatment with PG and treatment with PAM plus PG. From the rapid drop in the IR of the control and the low value of the final IR it is evident that both the harma and the loess are susceptible to surface sealing (BEN HUR et al. 1985).

When the same soils were exposed to rain without impact energy, the IR of the hamra soil was determined by the intensity of the mist (fig. 2) which indicates that the IR of the soil was maintained at values >35 $mm \cdot h^{-1}$. Similarly, the IR of the loess with ESP 2.8 decreased very slightly and gradually to a final IR of 31 $mm \cdot h^{-1}$. It is evident that when mist was applied, the mechanical breakdown of soil aggregates at the soil surface and seal formation are prevented and the IR is controlled by the HC of the soil layer.

The IR of the soils treated with PG dropped less rapidly than that of the control, and the final IR was higher (fig. 2).

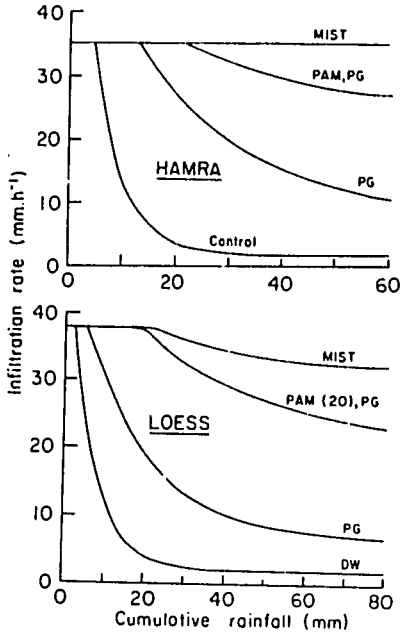

Fig. 2: *The infiltration rate (IR) of the hamra (18% clay) and loess exposed to simulated distilled rain water as a function of cumulative rainfall.*

The following treatments were applied:
(i) high energy rain of DW,
(ii) DW rain with no impact enrgy (mist),
(iii) phosphogypsum (PG) spread at the soil surface at 5 ton·ha^{-1} prior to the rain,
(iv) polyacrylamid (PAM, 20 kg·ha^{-1}) and PG (5 ton·ha^{-1}) were spread at the soil surface, prior to the rain.

Treatment		Mitra-Pg	Al Alvalade	V_v Vale Formoso	Loess	Hamra (18% clay)
Control	FIR mm·h^{-1}	4.8	3.8	5.6	2.0	1.7
	Runoff, mm	53	55	52	56	56
	Sed. conc. %	0.32	0.42	0.38	0.94	0.74
	Soil loss g·m^{-2}	170	231	198	527	416
Phosphogypsum	FIR mm·h^{-1}	8.8	8.8	10.0	6.8	11.3
	Runoff, mm	45	44	43	35	28
	Sed. conc. %	0.28	0.37	0.35	0.47	0.54
	Soil loss, g·m^{-2}	126	163	150	164	152
PAM + PG	FIR mm·h^{-1}	32	25	29	10.0	7.0
	Sed. conc. %	0.12	0.20	0.20	0.1	0.1
	Soil loss, g·m^{-2}	38	50	58	10	7
Mist	FIR mm·h^{-1}	22.0	26.5	23.4	31.0	35.0
	Runoff, mm	22	10	17.5	5.6	0
	Sed. conc. %	0	0	0	0	0
	Soil loss, g·m^{-2}	0	0	0	0	0

Tab. 3: *Infiltration rate, runoff and erosion from Israeli and Portuguese soils (in 70 mm rainstorm).*

13

PG reduced surface sealing by increasing the electrolyte concentration at the soil surface. In the PG treatment soils the seal is slow to form and is more permeable than the seal of the untreated soils.

Application of PAM in combination with PG increased the infiltration of rain (fig. 2). Applying PAM raised the final IR of the soils (fig. 2) from 2 mm·h^{-1} to 23.6 and 27.3 mm·h^{-1} for the loess and hamra soils, respectively. Similarly, PAM increased the cumulative infiltration of the loess from 14 to 60 mm and that of the hamra from 14 to 63 mm.

The IR curves of the soils from Portugal exposed to the same treatments as the soils from Israel are presented in fig. 3 and tab. 3. The following characteristics may be noted:

(i) The three soils are very susceptible to sealing when exposed to simulated rain. The IR of the three soils dropped sharply to final IR values of 4.8, 3.8 and 5.6 mm·h^{-1} for the Mitra, Alvalade and Vale Formoso soils, respectively. These soils have an unstable structure which disperse readily in spite of the low percentage of exchangeable sodium in the soil samples. The low percentage of clay which usually acts as a cementing material stabilizing soil aggregates, the relatively high percentage of silt which weakens the soil structure, and the low percentage of organic matter account for the instability of the soil structure and its high susceptibility to sealing.

(ii) There was a rapid drop in IR even when mist was applied (fig. 3). This drop in IR is due to the low HC of these soils (tab. 2 and fig. 1). The final IR with the mist was maintained at values ranging between 22 and 26mm·h^{-1}, compared with values exceeding 35 mm·h^{-1} for the hamra soil. The silty texture of the Portuguese soils was responsible for the low IR values obtained when misted upon.

(iii) Phosphogypsum was effective in stabilizing the soil surface of the three soils from Protugal (fig. 3). In spite of the low percentage of sodium in the exchange complex of these soils electrolytes prevented clay dispersion and seal with higher IR values was obtained.

(iv) The treatment with PAM + PG was quite effective in maintaining high IR. PG prevented clay dispersion and PAM was effective in binding the soil particles into aggregates. The final IF of the three soils treated with PAM ranged between 12 and 14.8 mm·h^{-1}.

(v) PAM plus PG treatment was more beneficial on the smectitic soils from Israel. It is also seen that PAM was less effective on the silty loess than on the hamra soil with 18% clay. It seems that PAM treatments in soils rich in kaolinite and silt are less beneficial. The interaction between soil texture clay mineralogy and PAM treatments in stabilizing soil structure should be further studied.

6 Runoff and erosion in Israeli and Portuguese soils

The final IR (FIR), runoff (in mm), sediment concentration (in %), and total soil losses from the two soils from Israel and three soils from Portugal when exposed to 70 mm rainstorm, are summarized in

14

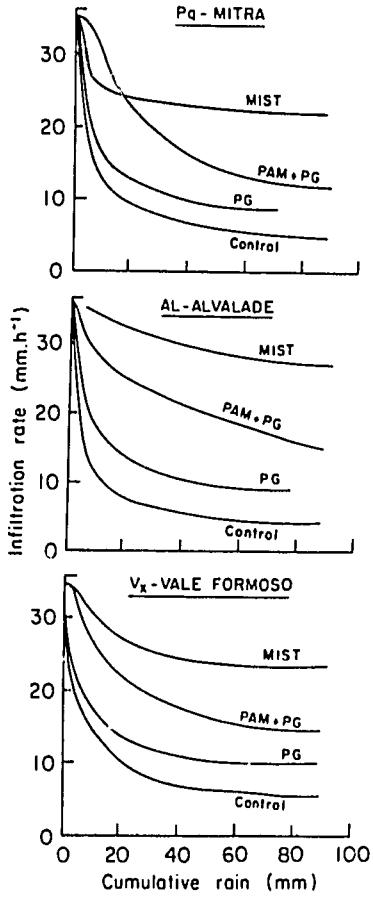

Fig. 3: *The IR of the three Portuguese soils as a function of cumulative rain.*

The treatments were:
(i) DW rain (control),
(ii) rain with no impact energy (mist),
(iii) PG spread at the soil surface (5 ton·ha^{-1}) prior to rain,
(iv) PAM plus PG spread at the soil surface prior to rain.

tab. 3. The following observations were made:

I) The final IR of the Israeli soils (control) were lower than the corresponding values of the soils from Portugal. Conversely, the amount of runoff of the five soils was similar.

This was due to the more rapid drop in IR of the soils from Protugal. Since the HC of the soils from Portugal was low, their initial IR was low and runoff started at lower values of rain depth (figs. 2 and 3). The high initial runoff in the soils from Portugal compensated for the lower final IR of the soils from Israel.

II) The loess and hamra soils from Israel are much more erosive than the

soils from Portugal (tab. 3). The sediment concentrations in the runoff from the loess and hamra were 0.94 and 0.74%, respectively, compared with 0.32–0.42% sediments in the runoff from the Portuguese soils. Accordingly, soil losses from the loess and hamra soils, in 70 mm rainstorms, were 527 and 416 $g \cdot m^{-2}$ compared with 170–231 $g \cdot m^{-2}$ for the Portuguese soils. The high erosivity of the Israeli soils is probably due to the mineralogy of the soil clays. Whereas the dominant clay in the Israeli soil is smectite which is quite dispersive, the dominant clay in the soils from Portugal is the less dispersive and less erosive kaolinite. The erosion data are in good agreement with the HC data (fig. 1).

III) PG seems to be more effective with the soils from Israel. Spreading PG increased the final IR of the loess and hamra by 3.4 and 6.6, respectively. The respective PG effect on final IR of the soils from Portugal ranged between 1.78 and 2.3. Similarly, the effect of PG on soil losses was more pronounced on the soils from Israel than on those from Portugal (tab. 3). Again, the Israeli soils, being more dispersive because of their higher ESP and smectitic mineralogy, were also more responsive to gypsum application.

IV) The dramatic effect of PAM + PG treatment on the infiltration runoff and erosion from the soils from Israel is very pronounced. Treatment with the soil conditioner increased the final IR of the loess and harma by the factors of 11.8 and 16.1, respectively. The corresponding values for the Portuguese soils ranged between 2.5 and 3.9 only. In the Portuguese soils the initial HC is low (tab. 2), the effect of seal formation on the IR is not so pronounced (fig. 3) and, accordingly, the effect of stabilizing the soil structure and preventing seal formation will be relatively small. The differences in the effect of PAM treatments on soil losses from the five soils is explained in the same way. However, it should be emphasized that although the effect of PAM on runoff and erosion from the soils of Portugal is not so pronounced as on the Israeli soils, it is still very marked and PAM plus PG treatment decreased runoff and erosion of the Portuguese soils by 0.42–0.60 and 0.22–0.29, respectively. The beneficial effect of PAM in preventing runoff and erosion should be tested in Portugal in field trials.

V) When rain without impact energy was applied (mist), seal was not formed and runoff and erosion were slight in the five soils. Mulching the soil and intercepting the impact of raindrops is the most effective treatment for reducing runoff and erosion and should be practiced wherever practical.

Many arable soils in the semi-arid regions of the world contain 0–30% clay and <3% exchangeable sodium in the upper layer. Until recently such levels of sodicity were not considered harmful to soil physical properties. This study demonstrated that the soil surface exposed to rain was particularly vulnerable to aggregate dispersion and seal formation because of the mechanical impact of raindrops and the low concentration of electrolytes in the rainwater.

16

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17

Appendix 2

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WATER QUALITY AND PAM INTERACTIONS IN REDUCING SURFACE SEALING[1]

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Seals formed at the soil surface during rainstorms reduce rain penetration and cause runoff and erosion. We studied the effect of surface application of an anionic polyacrylamide (PAM) at rates of 10, 20, and 40 kg·ha^{-1} on the infiltration rate (IR) of two soils, a loess (Calcic Haploxeralf) and a grumusol (Typic Chromoxerert), during simulated rainstorms. We determined the interaction between PAM and electrolyte concentration at the soil surface under a simulated rainfall of distilled water or tap water and by spreading gypsum. Electrolytes in the soil solutions that flocculated the soil clay enhanced the beneficial effect of the polymer on aggregate stability and greatly reduced water losses. Complete drying of the polymer-soil surfaces improved the binding action of the polymer.

Treatments with PAM under optimal conditions increased the final IR of the loess from 2.0 to 23.5 mm·h^{-1} and increased rain intake of an 80-mm rainstorm from 12.3 to 64.2 mm. PAM treatment of the grumusol increased the final IR from 3.0 in the control to 29.5 mm·h^{-1} and the rain intake from 21.3 to 62.3 mm. As soils from semiarid regions are unstable, form crusts, and produce much runoff (~80%) during rainstorms, the use of PAM to reduce runoff should be considered.

The formation of a seal at the soil surface, especially due to the action of raindrops but also as a result of sprinkler irrigation (Aarstad and Miller 1973), is a common feature of many soils, particularly in arid and semiarid regions. Surface seals are thin (<2 to 3 mm) and are characterized by greater density, finer pores, and lower saturated conductivity than the underlying soils. Soil seals have an important effect on many soil phenomena, reducing infiltration, increasing runoff and erosion, and interfering with seed germination.

Seal formation in soils exposed to rain is due to two complementary mechanisms: (1) physical disintegration of soil aggregates and their compaction caused by the impact of the raindrops at the soil surface and (2) chemical dispersion and movement of clay particles into a region of <1.0-mm depth below the soil surface, where they lodge and clog the conducting pores forming the "washed-in" layer (Agassi et al. 1981; McIntyre 1958). The chemical mechanism supplements the physical one under dispersive conditions (i.e., in sodic soils with low electrolyte concentrations in the soil solution).

Naturally occurring soil polymers, especially humic substances and polysaccharides, play an important role in promoting and maintaining soil structure. Since the introduction of synthetic polymers for soil conditioning in the early 1950s, there has been considerable interest in the mechanisms by which these materials bind to the soil colloidal constituents and in the mechanics of stabilizing aggregates. In general, soil conditioners were not cost-effective for general agricultural purposes where stabilization of the plough layer was required. However, polymers can be effectively used as anticrusting agents where it is necessary only to stabilize the aggregates at the soil surface.

We studied the effect of the application of a low-charge (20% hydrolysis) anionic polyacrylamide with a high molecular weight (PAM) at rates of 10, 20, and 40 kg·ha^{-1} on the infiltration rate (IR) during rainstorms. Following Bradfield's (1936) statement that "granulation is flocculation plus," it was assumed that stable aggregate formation requires the cementation by the polymer of flocculated soil colloids. The assumption was tested by combining PAM application with rain that contained electrolytes and by spreading phosphogypsum (PG) on the soil surface before distilled water rainfall. PG is a byproduct of the phosphate fertilizer industry

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-19-

with a dry composition of 97% $CaSO_4$ and 0.6% P_2O_5. PG dissolves readily and maintains Ca^{2+} and SO_4^{2-} concentration above 5 mol·m^{-3} (Agassi et al. 1986). Because the adsorption of polyanion by clay minerals depends on dehydration of the clays (Theng 1982), we also studied the effect of complete drying before the rain application.

MATERIALS AND METHODS

We used the air-dried <4-mm aggregates of a typical loess (Calcic Haploxeralf) from Bet Qama and of a dark brown grumusol (Typic Chromoxerert) from Sede Yoav in this study. Some chemical and physical properties of the soils are given in Table 1.

We packed soil samples to a depth of 2 cm in 30- × 50-cm perforated metal trays over 8 cm of coarse sand (four replications). We applied PAM treatments by spraying solutions with a 0.5-g·liter^{-1} concentration in distilled water onto the soil surface uniformly. PAM solutions of higher concentration could be prepared, but their viscosity was too high to be hand-sprayed conveniently. We applied PAM solutions in 2.0-liter·m^{-2} portions (equivalent to 10 kg·ha^{-1}), with a period of drying (~1 hour) between applications when necessary. This method of application assured that the polymer was concentrated in the surface layer of the soil. Control treatments received a similar volume of distilled water instead of PAM solution. We studied PAM treatments of 0, 10, 20, and 40 kg·ha^{-1} with the loess. With the grumusol, we studied only the 0- and 20-kg·ha^{-1} levels of application.

In most treatments, we allowed the soil treated with PAM solutions to dry completely by placing the trays in the sun for 24 h. We evaluated the effect of complete drying by comparing this "dry" treatment with a partially dried treatment in which the soil was left to dry for 24 h in the shade.

After the application of PAM solution, we placed the trays in a rainfall simulator (Morin et al. 1967) at a slope of 5% and saturated the soil in the trays slowly from below with tap water. At the end of the saturation process, we allowed the soil to drain and subjected it to a simulated rainfall with an intensity of 38 mm·h^{-1}. The designed "rainstorm" depth was 80 mm. In most studies distilled water (DW) was used to simulate rainwater. Typical mechanical parameters of the applied "rain" were: raindrop median diameter = 1.9 mm, median drop velocity = 6.02 m·s^{-1}; the kinetic energy was 19.3 J·mm^{-1}m^{-2}. We measured the volume of effluent, collected from outlet pipes set in the corners of the boxes, during the rainstorm and calculated the IR and final IR. Curves were fitted to the infiltration data ($R^2 > 0.98$) using a Hortonian type equation

$$I_t = I_f + (I_i - I_f)\cdot\exp(-gp)$$

where I_t is in the infiltration rate
I_f is the infiltration rate at equilibrium
I_i and g are constants
p is the amount of cumulative rainfall

We measured and analyzed the depth of water that percolated into the soil during the application of 80 mm of rainfall (cumulative infiltration) for each soil and separated means that differed significantly at the 5% level, using the Tukey test (Rubbins and van Ryzin 1975).

To study the effect of electrolyte concentration on the IR, we spread powdered PG at a rate of 5 tons·ha^{-1} over the soil before the distilled water rainstorm. Instead of DW, we also used tap water (TW) (EC = 0.97 dS·m^{-1}, SAR = 2.5) as a source of electrolytes in two rain simulation experiments. We took samples of runoff water during the rainstorm and measured the electrical conductivity (EC). The EC of the percolating water was estimated from these measurements (Agassi et al. 1986). As will be shown, the effect

TABLE 1

Some physical and chemical properties of the soils used

Soil	Classification	Particle size distribution (International Standards)			$CaCO_3$	CEC	ESP
		Sand	Silt	Clay			
		%				cmol$_c$·kg^{-1}	%
Loess, Bet Qama	Calcic Haploxeralf	50.0	31.0	19.0	11.0	14.5	5.0
Grumusol, Sede Yoav	Typic Chromoxerert	32.0	28.0	40.0	10.4	29.5	2.5

20

of PG and TW treatments on IR was similar in the short term.

We determined the stability of the treatment with PAM in subsequent storms by exposing the treated soil samples to three consecutive storms with a drying interval of 1 wk between rainstorms. The second and third rainstorms were of 60 mm each.

RESULTS AND DISCUSSION

Infiltration studies

The data from all experiments conducted are given in Table 2. The effect of PAM application on the IR of the loess is presented in Fig. 1 for the control (i.e., soil not treated with PAM) and for PG-treated soil. From the rapid drop in the IR of the control and the low value of the final IR, it is evident that the loess is susceptible to surface sealing. Soils that contain 19% clay and less than 1% organic matter and have an exchangeable sodium percentage (ESP) of 5 are known to be unstable and prone to sealing and crusting (Ben Hur et al. 1985). The impact of the raindrops combined with the absence of electrolytes in the rainwater caused the IR of the soil to fall from the initial rate of approximately 50 $mm \cdot h^{-1}$ to a final IR of 2.0 $mm \cdot h^{-1}$. The IR of the soil treated with PG dropped less rapidly than that of the control, and the final

TABLE 2

Infiltration and runoff data

Treatments	Beit Qama Loess			Sede Yoav Grumusol		
	FIR,[a] $mm \cdot h^{-1}$	CI,[a] mm	Runoff,[b] %	FIR, $mm \cdot h^{-1}$	CI, mm	Runoff, %
1st Storm[c]						
DW, PAM (0)	2.0	12.3	84.6 a	3.0	21.3	73.4 a
DW, PAM (10)	5.9	29.1	63.6 de			
DW, PAM (20)	6.5	38.3	52.1 g	7.4	41.9	47.6 c
DW, PAM (40)	6.5	39.0	51.3 g			
DW, PAM (20)[d]	5.2	17.4	78.3 b			
TW, PAM (0)	3.6	16.8	79.0 b			
TW, PAM (20)	15.0	56.2	29.8 i			
PG, PAM (0)	6.8	31.5	60.6 ef	9.7	36.3	54.6 b
PG, PAM (10)	15.7	49.4	38.3 h			
PG, PAM (20)	23.5	64.2	19.8 j	20.5	62.3	22.1 d
PG, PAM (40)	23.9	65.1	18.6 j			
PG, PAM (20)[d]	11.2	27.3	65.9 cd			
2nd Storm						
DW, PAM (0)	2.7	9.4	84.3 a	3.6	13.9	76.8 a
DW, PAM (20)	4.7	20.0	66.7 b	7.5	31.1	48.2 b
PG, PAM (0)	6.4	19.8	67.0 b	8.6	25.1	58.2 b
PG, PAM (20)	12.5	39.0	35.0 c	9.9	37.5	37.5 c
3rd Storm						
DW, PAM (0)	2.5	8.6	85.7 a	3.9	15.3	74.5 a
DW, PAM (20)	5.0	17.6	70.7 b			
PG, PAM (0)	5.9	15.2	74.7 b	9.5	27.9	53.5 b
PG, PAM (20)	6.3	25.3	57.8 c	11.8	33.1	44.8 b

[a] FIR = final infiltration rate; CI = cumulative infiltration.

[b] Letters after runoff figures which are the same denote treatments within storms which are not significantly different at the 5% level according to the Tukey test (Rubbins and van Ryzin 1975).

[c] PAM applications in $kg \cdot ha^{-1}$; DW = distilled water; TW = tap water; PG = phosphogypsum (5 $tons \cdot ha^{-1}$).

[d] Incomplete drying treatments.

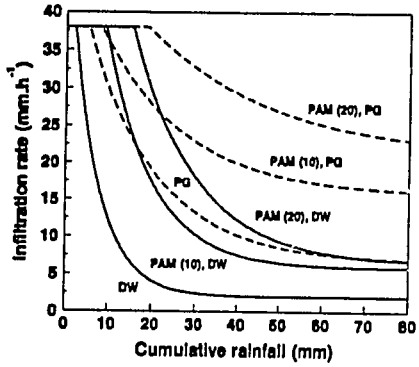

FIG. 1. Infiltration rate of loess as a function of cumulative rainfall, the level of PAM application (10, 20, and 40 kg·ha^{-1}) under distilled water (DW) rainfall and phosphogypsum (PG) (5 ton·ha^{-1}) treatments.

IR was higher (Fig. 1). PG reduced surface sealing by raising the electrolyte concentration in the solution at the soil surface, thus reducing clay dispersion and the formation of the "washed in" layer (Gal et al. 1984; Agassi et al. 1986). Thus, in the PG-treated soils the seal is slow to form and is more permeable than the seal of the untreated soils.

Application of PAM increased the infiltration of rain (Fig. 1). Applying PAM at 10, 20, and 40 kg·ha^{-1} increased the final IR of the soil (Table 2) approximately threefold. Similarly, PAM increased the cumulative infiltration of the soil by almost four times at the highest level of application. At rates above 20 kg·ha^{-1}, the effect of additional PAM was insignificant (the curves are not presented), although this may have been because of the difficulty, experienced during application, of keeping the PAM in the upper layer of the soil.

The dramatic effect of PAM in combination with PG is also presented in Fig. 1. PG increased the final IR of the loess treated with PAM, 20 kg·ha^{-1}, by 10 times (Table 2). Similarly, runoff from an 80-mm rainstorm dropped from 84.6% in the control to only 18.8% and 51.8% when treated with PAM, 20 kg·ha^{-1}, with and without PG, respectively. It is evident that PAM is much more effective in the presence of PG at the soil surface. Similar phenomena were observed by Shaviv et al. (1985). PG spread at the soil surface dissolves and increases the electrolyte concentration in the soil solutions to values above the flocculation value of the clays (Oster et al. 1980 Flocculation of the soil clay is a precondition fc the cementing and stabilization of aggregates a the soil surface (Bradfield 1936).

The beneficial effect of PAM on the IR de pends upon the application conditions and th quality of the applied "rainwater." In Fig. 2 (and b), PAM at the optimal rate of 20 kg·ha⁻ was applied to the loess under the followin conditions: (1) PAM was sprayed onto the so and the trays were either completely dried o only partially dried and (2) DW or TW rainfal was applied. Complete drying increased the ben eficial effect of the polymer. It is evident fron the data given in Table 2 that complete dryin of the PAM and PG treatment more than dou hled the final IR and the cumulative infiltratior values compared with incomplete drying.

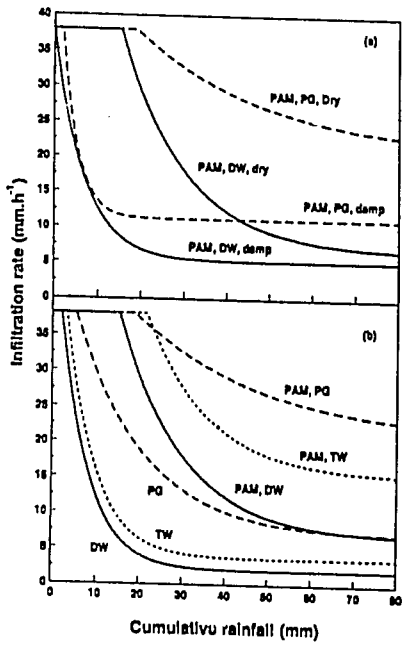

FIG. 2. Infiltration rate of loess treated with PAM, 20 kg·ha^{-1} as a function of cumulative rainfall and the drying treatments of PAM (a) and the electrolyte concentration in the applied water (b) (TW = tap water and DW = distilled water). PG represents treatment with phosphogypsum at 5 ton·ha^{-1}; PAM represents treatment with polyacrylamide polymers at 20 kg·ha^{-1}

22

The effect of drying in increasing the efficiency of the polymer in stabilizing the aggregates and preventing crust formation is explainable by the bonding mechanism between the anionic polyelectrolyte and the negative clay (Theng 1979). It is suggested that two types of cation-bridging are responsible for the polymer adsorption and the binding of clay platelets. In the first type, an anionic group of the polymer interacts with an exchangeable cation through a water molecule to yield an 'outer-sphere" complex. This mode of bonding is obtained in aqueous systems. The second type of cation bridging may occur under dehydrated conditions. In this instance, an anionic group of the polymer is directly associated with an exchangeable cation to form an "inner-sphere" complex. Inner-sphere complex formation involves the displacement (from the interface to the bulk solution) of numerous water molecules by a single polyanion chain. The resultant gain in entropy (0.3 to 0.5 $kJ \cdot mol^{-1}K^{-1}$) has a promoting effect on adsorption. In addition, the uncharged segments of the adsorbed chain may interact with each other and with the surface through van der Waals forces. Drying induces inner-sphere complex formation and van der Waals interactions; this would explain why air drying leads to a marked increase in the water stability of soil aggregates.

The electrolyte effect on PAM effectiveness is demonstrated by the PG treatment and by the effect of raining with TW (Fig. 2b). The concentration of electrolytes in TW increased the IR values of the control (no PAM) (Table 2). However, PG was more effective in increasing the IR than was TW. The electrolyte concentration in the effluent of PG-treated soils was 1.2 to 1.4 $dS \cdot m^{-1}$, compared with an EC of 0.97 $dS \cdot m^{-1}$ for the TW. The increase in electrolyte concentration in the PG-treated soil compared with TW partially explains the increase in the IR values (Agassi et al. 1981). In addition to the electrolyte concentration effect, Agassi et al. (1986) also suggested that PG treatments interfere with the continuity of the seal and may act as a mulch and thus increase the IR of the soil beyond the electrolyte effect.

In the PAM treatments, the result of using TW instead of DW was more pronounced. In the soil untreated by PAM the use of TW increased cumulative infiltration by 4.5 mm, but in the PAM-treated soil the increase in cumulative infiltration was 18.1 mm. As the concentration of electrolyte in TW exceeds the flocculation value of the clay, the polymer acts efficiently as a cementing agent that stabilizes the soil aggregates, prevents seal formation, and maintains high IR values. The beneficial effect of PG, compared with TW, in the PAM treatments was similar to that with no PAM treatments. In the PG treatments the predominant cation in the soil solution is Ca^{2+}, whereas in TW Na^{+} and Ca^{2+} cations are present in similar concentrations. Sodium is known to substitute in the Ca-polymer bond and weaken the cation bridge between the polymer and clay surface (Theng 1979).

The flocculation effect of the electrolytes in the TW suggests that it may be necessary only to apply PG to soil treated with PAM under natural rainstorms to ensure stabilization of the soil aggregates. When irrigation water is applied by sprinklers, PAM alone will prevent seal formation and will be effective in maintaining high water penetration. The IR of the grumusol as a function of cumulative rain is presented in Fig. 3. The following should be noted:

The grumusol is less dispersive than the loess. The final IR of the loess was lower than that of the grumusol; the infiltration rate drops more steeply with cumulative rainfall resulting in a lower cumulative infiltration value (Table 2). The higher percentage of clay, which acts as cementing material, stabilizes the aggregates at the soil surface of the grumusol, slows their

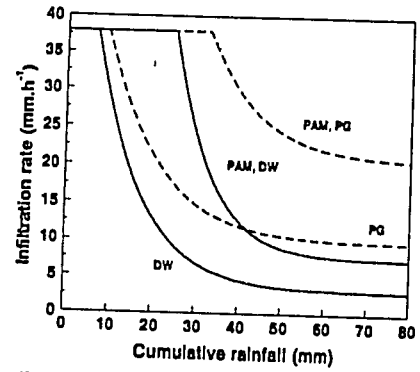

FIG. 3. Infiltration rate of grumusol as a function of cumulative rainfall, phosphogypsum treatment (PG, at 5 $ton \cdot ha^{-1}$, and PAM application (at 20 $kg \cdot ha^{-1}$). DW = distilled water.

23'

breakdown and the formation of a seal at the soil surface. Therefore, a seal is formed at the soil surface. Also, the ESP of the grumusol is lower than that of the loess (Table 1).

The beneficial effect of PG on the IR of the grumusol is similar to that in the loess in spite of the lower ESP of the grumusol. The higher percentage of clay in the grumusol explains the response of this soil to PG application (Katzman et al. 1983).

PAM, applied at a rate of 20 kg·ha^{-1} after complete drying, was quite efficient in stabilizing the soil aggregates at the soil surface and preventing sealing (Table 2). When PAM was applied with PG, its beneficial effect was much more pronounced. It is evident that treating the soil with a combination of PAM and PG produces the best results. For the soil conditioner to be effective, the soil clays must continue to be flocculated. PG dissolution supplies to the rainwater the electrolytes needed to attain these conditions.

Effect of consecutive storms

The amount of rain during a rainy season may exceed 80 mm, but the rain is not continuous and there are dry periods between rainstorms. Thus the question arises as to the effect of more rain and of dry intervals between rainstorms on the efficiency of PAM as an amendment. Morin and Benyamini (1977) studied the effect of drying for periods of 24 h, 6 days, and 11 days on the crust and IR. They found that the drying periods increased the initial IR but had no significant effect on the final IR. Their explanation was that the increase in the initial IRs in the second storm was due to crack formation in the crust. A drying period of 7 days was enough to break the crust completely. Thus, this interval was used in our study.

The effect of the second and third consecutive storms of 60 mm each on the efficiency of PG and PAM treatments in maintaining a high IR in the loess is presented in Table 2. The final IR and the percentage of runoff in the control and PG treatments were similar in the three storms. PG, spread at a rate of 5 tons·ha^{-1}, continued to be effective throughout the three storms (200 mm of rain). In a saturated solution the concentration of gypsum is 2 g·liter^{-1}. In the rain studies only 50% saturation was obtained; thus 200 mm of rain dissolved approximately 2 tons·ha^{-1}, and the PG was still present in sufficient quantities to be beneficial in the third storm.

The final IR in the PAM treatments (without PG) stayed the same in the first, second, and third storms (Table 2), whereas the runoff increased slightly in the three consecutive storms. It seems that the PAM-only treatment was comparable to the PG-only treatment and similarly maintained its stabilization effects throughout the three storms.

The effectiveness of the PAM + PG treatments was reduced over the three storms. Nevertheless, in the third storm the treatment still reduced runoff significantly in comparison to the separate treatments. Over the three storms the runoff percentage was only 36% compared with 85% from the control and 62% and 67% in the separate treatments of PAM and PG, respectively.

The PAM and PG treatment resulted in a similarly low runoff percentage of the grumusol. Here the overall figures for the storms were 75% for the control, 55% for the PG treatment, and 34% for the combination of PAM and PG.

CONCLUSIONS

The effect of application of dilute solutions of PAM at 20 kg·ha^{-1} on the infiltration rate and runoff of nonstable soils was very beneficial. Drying the polymer-soil surface and maintaining the electrolyte concentration in the soil solution, which flocculates the soil clays, enhance the binding action of the polymer and stabilize the aggregates at the surface. PAM combined with PG treatments at the optimal rate increased rain intake in the two soils by two to three times that of the control. Soils from semiarid regions are unstable and form seals that lead to about 80% runoff during the rainy season. The possible reduction of water losses by PAM and PG treatments to a fraction of this may prove to be greatly beneficial from both economical and environmental aspects and should be studied further.

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Appendix 3

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Water-Droplet Energy and Soil Amendments: Effect on Infiltration and Erosion

H. J. C. Smith, G. J. Levy,* and I. Shainberg

ABSTRACT

The impact energy of water droplets from rain or overhead sprinklers can cause a seal to form at the soil surface. This constitutes a severe problem in agricultural lands in the arid and semiarid regions. Spreading a soil conditioner on the surface of the soil and providing a constant supply of electrolytes may prevent seal formation. The effect of droplet impact energy and water quality on infiltration and erosion was studied, using a tank drip-type rain simulator, in a sandy loam soil (Typic Rhodoxeralf) treated with an anionic polyacrylamide (PAM) and phosphogypsum (PG). Three kinetic energies (KE) of 3-mm diameter drops were obtained by varying their falling heights. The two qualities of water were distilled water (DW) and tap water (TW), to simulate rain and irrigation water, respectively. Increasing the impact energy reduced the infiltration rate (IR), cumulative infiltration (rain intake), and soil erosion in all treatments. Addition of PAM in the presence of electrolytes (either PG or TW) increased both final IR and cumulative infiltration by 7- to 8-fold compared with the control, and was much more effective than PAM, PG, or TW alone. The PAM + electrolyte treatments decreased soil erosion by more than one order of magnitude compared with the control.

FORMATION OF A CRUST at the soil surface, generally due to the beating action of raindrops but also as a result of sprinkler irrigation (Aarstad and Miller, 1973), is a common feature of many soils, particularly in the arid and semiarid regions. Surface crusts are thin (<2–3 mm) and are characterized by greater density, finer pores, and lower saturated conductivity than the underlying soil. Soil crusts have a prominent effect on many soil phenomena, e.g., reduction of infiltration and increase in runoff (Morin et al., 1981) and interference with seed germination (Cary and Evans, 1974).

Crust formation in soils exposed to the beating action of falling drops is due to two mechanisms (Agassi et al., 1981; McIntyre, 1958): (i) physical disintegration of soil aggregates and their compaction caused by the impact action of drops hitting the soil surface; and (ii) a physicochemical dispersion and movement of clay particles into a region of 0.1 to 0.5-mm depth, where they lodge and clog the conducting pores. The first mechanism is very much determined by the KE of the drops (Moldenhauer and Kemper, 1969), while the second is controlled mainly by the concentration and composition of the cations in the soil and applied water (Agassi et al., 1981; Kazman et al., 1983). The two mechanisms act simultaneously with disintegration enhancing dispersion.

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One way of reducing crusting is to improve soil structure and aggregate stability at the soil surface. The possibility of using organic polymers, and especially PAM, to improve soil structure and reduce crust formation has recently been studied (Helalia and Letey, 1988a,b; Shainberg et al., 1990; Shaviv et al., 1986). Furthermore, it has been reported that the combined application of polymer and PG (an electrolytic stabilizer) had a more pronounced effect in improving infiltration than either application alone (Shainberg et al., 1990; Shaviv et al., 1986). Current interest in polymers as soil conditions is enhanced by their low price ($3 kg^{-1}) and application rate (20 kg ha^{-1}), which make their use in agriculture economically viable.

Our objective was to study the combined effect of various impact energies of water drops, stability of surface aggregates treated with PAM, and electrolyte concentration on seal formation and erosion.

MATERIALS AND METHODS

A noncalcareous sandy loam soil (Typic Rhodoxeralf) from the coastal plain of Israel, with a cation exchange capacity of 11.0 cmol$_c$ kg^{-1} and exchangeable sodium percentage (ESP) of 4.4, was used in this study. The texture was 18.0% clay, 5.0% silt, and 77.0% sand. Dominant clay minerals were kaolinite and montmorillonite.

Infiltration, runoff, and erosion were studied using a drip-type rain simulator, with a 750 by 600 mm closed water chamber placed in a adjustable-height raindrop tower. Rain was generated through hypodermic needles (~1000, arranged in a spacing of 20 by 20 mm), to form a known fixed droplet size. The average water-drop diameter was 2.97 mm $\pm$ 5 $\times$ 10^{-2} mm. Falling heights of 0.4, 1.0, and 1.6 m were used to obtain drops with various kinetic energies. The impact velocities of the drops falling from these heights were 2.5, 4.02, and 4.98 m s^{-1}, respectively, and their corresponding kinetic energies were 3.6, 8.0, and 12.4 J mm^{-1} m^{-2} (Epema and Riezebos, 1983). Rain intensity was maintained at 33 mm h^{-1} using a peristaltic pump.

Air-dried aggregates, crushed to pass through a 4.0 mm sieve, were packed in 200 by 400 mm trays, 20 mm deep, over a 5-mm thick layer of coarse sand. In the PAM treatment, the anionic low charge (20% hydrolysis) PAM with a high molecular weight (~10^7 g mol^{-1}) was used at a rate equivalent to 20 kg ha^{-1}. The PAM solutions with concentration of 0.5 g L^{-1} were sprayed on the soil surface in two portions of 2.0 L m^{-2} each, with 1 h of drying in between, thereby assuring the concentration of the polymer at the soil surface. Thereafter, the trays were allowed to dry for 24 h before raining was commenced. In the PG treatments, powdered PG at a rate equivalent to 5 Mg ha^{-1} was spread over the soil surface prior to rain. In most storms, DW was applied. In a few experiments, we used TW, with an electrical conductivity (EC) of 0.1 S m^{-1} and a sodium adsorption ratio (SAR) of 2.0.

After the various pretreatments, the trays were placed in the rainfall simulator at a slope of 15%, and saturated with TW prior to the rainstorm. During each storm the volume of runoff water and of water percolating through the soil was

21

recorded. Sediment concentration in the runoff was measured by drying, and the amount of soil loss was calculated. Three replicates for each treatment were performed concurrently.

The IR data obtained from the rainfall simulator were analyzed as described by Levy et al. (1988), using a nonlinear regression equation proposed by Morin and Benyamini (1977).

RESULTS AND DISCUSSION

Infiltration Studies

The calculated infiltration curves for the various treatments are presented in Fig. 1. A coefficient of determination (R^2) between paired calculated and measured IR values was >0.95 in all treatments.

The effect of PAM application in combination with DW, TW, and PG on the IR of the sandy loam soil exposed to raindrops with KE of 12.4 J mm^{-1} m^{-2} (falling height = 1.6 m), is presented in Fig. 1a. Exposing the untreated soil to DW rain resulted in a rapid drop in the IR, to a very low final IR value (1.8 mm h^{-1}), indicating that the soil is unstable and susceptible to surface sealing. Ben-Hur et al. (1985), who studied seal formation in soils exposed to high energy rain (18.6 J mm^{-1} m^{-2}), characterized soils with medium clay content (~20%), low organic material, and moderate ESP (~5) as tending to form seals with low permeability when exposed to DW rain. Our results are in good agreement with these observations and suggest further that seals in unstable soils can form at lower energies than those used by Ben-Hur et al. (1985).

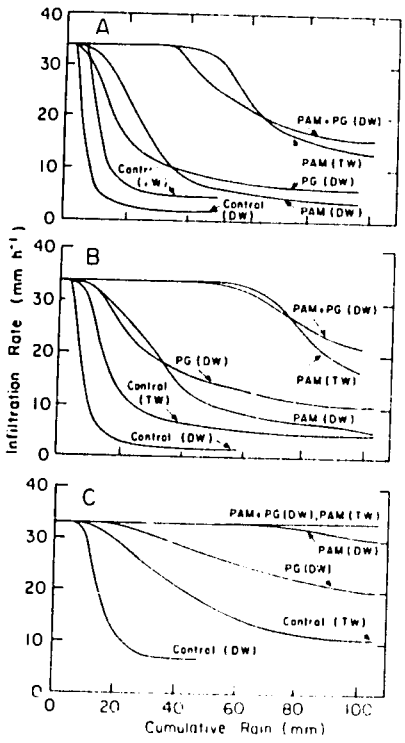

Fig. 1. Infiltration rate of soil as a function of cumulative rain for three kinetic energy levels of rain: (A) 12.4, (B) 8, and (C) 3.6 J mm^{-1} m^{-2}. Treatments: PAM = anionic polyacrylamide; PG = phosphogypsum; DW = distilled water; TW = tap water.

Increasing electrolyte concentration at the soil surface either by spreading PG at the soil surface or by using TW resulted in a more moderate decrease in the IR and higher final IR values compared with those in the untreated soil (Fig. 1). Phosphogypsum at the soil surface dissolves quite readily during the rainstorm and releases Ca^{2+} and SO_4^{2-} ions into the soil solution to support a concentration (23 mmol$_c$ L^{-1}) high enough to prevent clay dispersion (Gal et al., 1984). When applying TW containing 4 mM L^{-1} of Na and 2.5 mM L^{-1} of Ca, the IR values were lower than those obtained with PG. It has been postulated (Agassi et al., 1985) that the PG particles interfere with the continuity of the seal and thus increase the seal's permeability more strongly than the PG prevents clay dispersion. In both treatments, PG and TW, which prevent chemical clay dispersion by maintaining the electrolyte concentration at the soil surface above the flocculation value of the clay, resulted in a seal formation that was due predominantly to the impact energy of the drops. Thus, a seal was formed with a permeability higher than that of the untreated soil.

Application of PAM (20 kg ha^{-1}) to the soil and then exposing it to DW rain increased the final IR to 3.6 mm h^{-1}, compared with 1.8 mm h^{-1} in the untreated soil. The cumulative infiltration, in an 80-mm storm, was 32.1 mm, similar to that obtained in the PG treatment (31.1 mm). However, combining the PAM application with spreading of PG or using TW (i.e., increasing the electrolyte concentration at the soil surface) led to a marked increase in the IR curves, and consequently to high final IR values; these reached 12.9 and 15.4 mm h^{-1} for the PAM + TW and PAM + PG treatments, respectively (Fig. 1a). Our results reinforce those obtained by Shainberg et al. (1990) and Shaviv et al. (1986), and indicate that, for PAM to be effective in stabilizing soil structure and improving infiltration, prior flocculation of the clay particles by electrolytes is essential.

The effect of lower impact KE of water drops (8 and 3.6 J mm^{-1} m^{-2}; falling heights of 1.0 and 0.4 m respectively) on IR of the soils with the various treatments is presented in Fig. 1b and 1c, and Tables 1 and 2. Basically the effect of chemical treatments for medium and low impact KE was similar to that for the high-KE rain. However, the following should be noted:

Table 1. Mean measured final infiltration rate (FIR) for three levels of raindrop energy and chemical treatments.

Chemical treatment†		Level of energy, J mm^{-1} m^{-2}		
		3.6	8.0	12.4
		FIR, mm h^{-1}‡		
PAM + PG,	DW	33.6 ± 0.52a	18.4 ± 0.89a	15.4 ± 1.09a
PAM,	TW	33.6 ± 0.65a	16.0 ± 0.23b	12.9 ± 0.82b
PG,	DW	19.8 ± 0.47c	10.0 ± 0.31c	5.0 ± 0.41c
Control,	TW	10.5 ± 0.37d	4.1 ± 0.26d	4.1 ± 0.29d
PAM,	DW	29.8 ± 0.71b	3.6 ± 0.27d	3.6 ± 0.32d
Control,	DW	6.8 ± 0.19e	1.5 ± 0.22e	1.8 ± 0.21e

† PAM = anionic polyacrylamide; PG = phosphogypsum; DW = distilled water; TW = tap water.

‡ Means ± LSD. Within columns, means followed by the same letter do not differ significantly at the 0.05 level, using Tukey's test (Rubbins and van Ryzin, 1975).

28

Table 2. Mean calculated cumulative infiltration rate (CIF) after 80 mm of rain for three levels of raindrop energy and chemical treatments.

Chemical treatment†		Level of energy, J mm^{-1} m^{-2}		
		3.6	8.0	12.4
		CIF, mm‡		
PAM + PG,	DW	80.0 ± 3.52a	76.6 ± 1.79a	64.6 ± 1.17a
PAM,	TW	80.0 ± 2.35a	77.8 ± 1.83a	67.1 ± 1.02a
PG,	DW	67.6 ± 2.41b	47.6 ± 1.52b	31.1 ± 0.81b
Control,	TW	50.4 ± 2.57c	26.0 ± 1.21d	18.9 ± 0.46c
PAM,	DW	79.4 ± 3.31a	38.4 ± 1.37c	32.1 ± 0.92b
Control,	DW	28.3 ± 2.24d	10.8 ± 1.12e	9.1 ± 0.33d

† PAM = anionic polyacrylamide; PG = phosphogypsum; DW = distilled water; TW = tap water.
‡ Means ± 1 SD. Within columns, means followed by the same letter do not differ significantly at the 0.05 level, using Tukey's test (Rubbins and van Ryzin, 1975).

1. For the same chemical treatment, as the impact KE of the drops decreased, the IR of the soil declined more slowly and the final IR was maintained at a higher value.
2. Irrespective of the electrolyte concentration in the soil solution, an impact KE of 4 J mm^{-1} m^{-2} was not enough to form a seal in a PAM-treated soil (Fig. 1c). The rate of rain intake by the soil exceeded rain intensity, and the IR of the soil was controlled by rain intensity rather than by seal properties.

The effects of drop impact KE on the final IR for each chemical treatment are presented in Fig. 2. In some of the treatments there were no significant differences (at the 0.05 probability level) in the final IR values between the medium- and high-KE rain and, where differences were observed, they were fairly small (Fig. 2). On the other hand, large differences in the final IR values were noted between the low- and medium-KE rain, ranging from two- to sixfold. It is thus evident that the sandy-loam studied is very unstable and a medium-KE rain of 8 J mm^{-1} m^{-2} is enough to form a fully developed seal.

Smaller differences between the different levels of KE within each treatment are observed when looking at the cumulative infiltration for a storm of 80 mm (Fig. 3). By contrast to the final IR, cumulative infiltration is an integrated value that reflects the rate at which the IR decreases with increasing depth of rainfall. Our results indicate that in the PAM treatments supplemented with PG or TW (PAM + electrolytes), small differences were observed in the cumulative infiltration when changing the KE of the rain. Cumulative infiltration was always >70 mm for these treatments; hence, >80% of the rain applied entered the soil, compared with <40% in the untreated soil (Fig. 3). The reason is that, during 80 mm of rain, hardly any change in the IR was noted, suggesting that PAM + electrolytes is a beneficial treatment with respect to improving infiltration and soil structure, irrespective of the KE of the rain. Adding only PAM to the soil and applying DW rain resulted in cumulative infiltration values similar to those of the PG and TW alone in the medium- and high-KE rains. In the low-KE rain (3.6 J mm^{-1} m^{-2}), however, cumulative infiltration in the PAM treatment was similar to that of PAM + electrolytes. It may be concluded that at low KE rain, the cementing effect of PAM itself, which supports

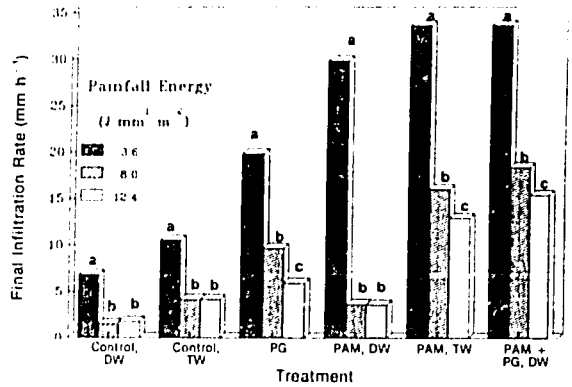

Fig. 2. Final infiltration rates for three kinetic energy levels of rain. Within treatments, bars labeled with the same letter do not differ significantly at the 0.05 level, according to Tukey's test (Rubbins and van Ryzin, 1975). Treatments: PAM = anionic polyacrylamide; PG = phosphogypsum; DW = distilled water; TW = tap water.

stable aggregates at the soil surface, is more effective in enhancing high infiltration than are the PG and TW treatments.

It should be emphasized however, that because cumulative infiltration reflects the rate at which a seal is formed and hence the resistance of the soil to seal formation, it depends on a number of factors, such as aggregate size and stability (Gumbs and Warkentin, 1976) and initial soil water content (Levy et al., 1986). Thus, the cumulative values presented in Fig. 3 are useful for comparisons between treatments but cannot be used for comparisons with data obtained under different experimental conditions. The final IR, on the other hand, is a characteristic of the soil independent of the initial soil state (e.g., water content, packing, etc.).

Soil Erosion

Soil losses from 80-mm rainstorms are presented in Fig. 4. They clearly indicate that erosion increases with an increase in the KE of rain. In agreement with the infiltration results, the greatest amounts of soil losses were observed in the untreated soil exposed to DW rain, reaching 1436 g m^{-2} in the high energy rain. Electrolyte treatments alone (PG and tap water) were quite efficient in reducing erosion, compared with the control (Fig. 4). These treatments reduced soil losses to 20 to 50% of that of the control, being most effective in the low impact rain energy. Electrolytes are effective in reducing erosion because of the following: (i) runoff is reduced; (ii) particles larger than those in the untreated soil, which are more difficult to detach, are present at the soil surface; and (iii) enhanced sedimentation of entrained particles occurs. The PAM-treated samples, with the exception of the PAM-only treatment exposed to DW high-energy rain, were most effective in controlling soil erosion, irrespective of the KE of the rain. Soil losses in the PAM treatments were <5% of the losses observed in the control.

Considering the effect of droplet impact energies on formation and permeability of the seals (Fig. 2 and 3), an impact energy of 8 J mm^{-1} m^{-2} appears to be enough to form a seal at the surface of the studied soil when

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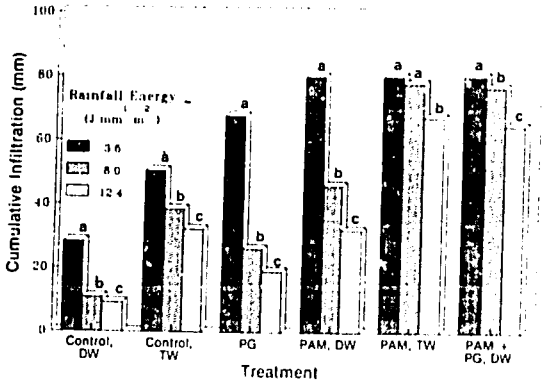

Fig. 3. Cumulative infiltration (for an 80-mm storm) for three kinetic energy levels of rain. Within treatments, bars labeled with the same letter do not differ significantly at the 0.05 level, according to Tukey's test (Rubbins and Ryzin, 1975). Treatments: PAM = anionic polyacrylamide; PG = phosphogypsum; DW = distilled water; TW = tap water.

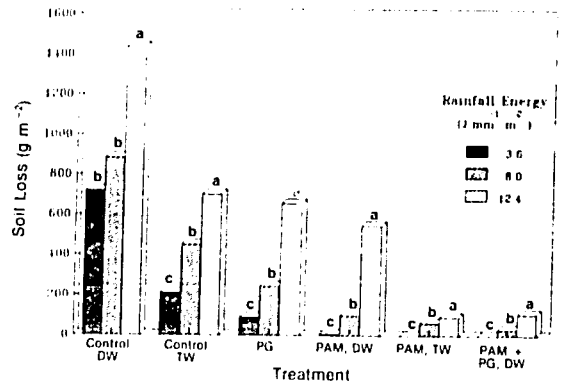

Fig. 4. Total soil loss after an 80-mm storm for three kinetic energy levels of rain. Within treatments, bars labeled with the same letter do not differ significantly at the 0.05 level, according to Tukey's test (Rubbins and van Ryzin, 1975). Treatments: PAM = anionic polyacrylamide; PG = phosphogypsum; DW = distilled water; TW = tap water.

the soil is rained upon with either DW or TW. Soil erosion, on the other hand, increased sharply with an increase in impact energy through the entire range of rain KE used (Fig. 4). This implies that particle detachment continued to increase after rain KE increased from 8 to 12.4 J mm^{-1} m^{-2}, despite the fact that the seal was already fully developed at the lower KE. We thus concluded that runoff and soil erosion are not directly related, and the one should not be predicted from measurements of the other. However, where there is no runoff there is no erosion, since runoff water is required to remove eroded material. Results of the PAM treatments, especially PAM + electrolytes, support this last statement, as hardly any runoff and consequently soil loss were observed in these treatments.

CONCLUSIONS

Seal formation, runoff, and soil loss were observed even under low impact KE (3.6 J mm^{-1} m^{-2}) in an untreated soil. Irrigating soils that are sensitive to low-energy rain leads to surface sealing and water and soil loss. Treating the soil with PAM + electrolytes (PG or TW) improves infiltration and reduces runoff and erosion under varying conditions of KE of the rain. It is suggested, therefore, that adding PAM at a rate of 20 kg ha^{-1} (amounting to a cost of \$60–70 ha^{-1}, in 1989 terms) to the surface of a soil irrigated with overhead sprinklers using irrigation water (EC >0.1 S m^{-1}) will markedly reduce seal formation and thus improve soil and water management.

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30

Appendix 4

Aust. J. Soil Res., 1991, **29**, 455–65

Rain Energy and Soil Amendments Effects on Infiltration and Erosion of Three Different Soil Types

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Abstract

The effect of rain kinetic energy and soil amendments on infiltration and erosion from three Israeli soils was studied using a drip-type simulator. The soil samples were from the top layer (0–250 mm depth) of cultivated fields differing in their texture, specific surface area and lime content. Three kinetic energies of raindrops were obtained by varying heights of fall ($h = 0 \cdot 4$, $1 \cdot 0$ and $1 \cdot 6$ m) of 3 mm diameter drops. The soil types studied were Typic Chromoxerert, Typic Rhodoxeralf and Calcic Haploxeralf. Soil amendments were phosphogypsum (PG) and a combined application of an anionic polyacrylamide (PAM) with PG. An increase in the impact energy of the raindrops reduced depth of rain before ponding, final infiltration rate (FIR), cumulative infiltration (i.e. infiltration parameters) and increased soil erosion. The addition of PAM+PG to the soil surface significantly increased the infiltration parameters and reduced erosion compared with the PG and control treatments. The Typic Chromoxerert was the least susceptible of the three soils to sealing, probably because of its high smectitic clay content, high specific surface area and high $CaCO_3$ content which stabilize soil structure. The Typic Rhodoxeralf with the lowest specific surface area was the most susceptible to clay dispersion, and seal formation. Relative to the Typic Chromoxerert and the Typic Rhodoxeralf, the Calcic Haploxeralf was intermediate in its susceptibility to seal formation.

Introduction

Seal formation at, and subsequent runoff and soil erosion from, soil surfaces exposed to the beating action of raindrops and overhead sprinkler irrigation are common features of many soils, particularly in the arid and semi-arid regions. Surface seals are thin layers (<2–3 mm) and are characterized by greater density, finer pores, and lower saturated conductivity than the underlying soil. Rainfall infiltration, runoff and erosion depend largely on the properties of the seal formed.

Seal formation in soils exposed to rain results from two mechanisms (McIntyre 1958; Agassi *et al.* 1981): (i) physical disintegration of soil aggregates and their compaction caused by the impact action of the drops hitting the soil surface; and (ii) dispersion of clay particles and their possible movement directly beneath the immediate surface where they lodge and clog conducting pores. The first mechanism is determined by the kinetic energy of the drops and the stability of the aggregates (Moldenhauer and Kemper 1969), while the second is controlled mainly by the concentration and composition of the cations in the soil and applied water (Agassi *et al.* 1981; Kazman *et al.* 1983). The two mechanisms act simultaneously, as the first enhances the second.

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32

The tendency of a soil to form a seal and erode depends on the stability of its structure which, in turn, depends on texture, clay mineralogy, exchangeable sodium percentage (ESP) and the presence of cementing agents such as organic matter, iron oxides, etc. (Kemper and Koch 1966). When Ben-Hur *et al.* (1985) tested soil stability in smectitic soils under conditions of simulated rain, they found that seal permeability depended on clay content. They reported a decrease in soil permeability with an increase in clay content up to 20% clay; further increases in clay content resulted in an increase in soil permeability. They postulated that the observed increase in seal permeability with an increase in clay content above 30% was a result of increased aggregate stability. Where the effect of silt content is concerned, results have not been conclusive. In some studies, high silt content was associated with low structural stability, high susceptibility to seal formation (Cary and Evans 1974), as well as high levels of erosion (Wischmeier and Mannering 1969). More specifically, Moldenhauer and Long (1964) obtained good agreement between silt content and the rate of surface sealing. Ben-Hur *et al.* (1985), on the other hand, showed that silt content had no effect on the final infiltration rate (FIR) of the seal. Regarding the rate of seal formation, Ben-Hur *et al.* (1985) found that the effect of silt depended on the mechanism governing seal formation. When the soils were exposed to saline water rain and impact energy of the drops (physical disintegration) predominated, an increase in silt content increased the rate of seal formation. But, when both the physical and chemical (clay dispersion) mechanisms took place, silt content had no effect on the rate of sealing (Ben-Hur *et al.* 1985).

One way of limiting seal formation is to control the chemical clay dispersion by maintaining the electrolyte concentration of the soil solution at the soil surface above the flocculation value of the soil clays (Agassi *et al.* 1981). This can be achieved by spreading phosphogypsum (PG) at the soil surface (Kazman *et al.* 1983; Agassi *et al.* 1986). The electrolyte concentration of a saturated PG solution is 25 mmol(+) L^{-1}, which is above the flocculation value of soil clays in arable soils. Another way of limiting seal formation and improving aggregate stability at the soil surface is the use of organic polymers. Their use, especially that of anionic polyacrylamide (PAM), for improving soil structural stability and reducing seal formation has been studied recently (Shaviv *et al.* 1985; Helalia and Letey 1988; Shainberg *et al.* 1990; Smith *et al.* 1990). In addition, it was reported that the combined application of a polymer and PG had a more pronounced effect than that of either one separately in improving infiltration (Shainberg *et al.* 1990; Smith *et al.* 1990).

The objective of this research was to study the role of raindrop impact energies in combination with soil amendments on infiltration, runoff and erosion in three dominant soils in Israel.

Materials and Methods

Samples from 0–250 mm depth of three cultivated smectitic soils were used in this study. The soils were a Typic Rhodoxeralf from Morasha, a Calcic Haploxeralf from Bet Qama, and a Typic Chromoxerert from Negba, Israel. Some physical and chemical properties of the soils are given in Table 1. Cation exchange capacities (CEC) of the soil samples were determined with sodium acetate buffered at pH 8·2 (U.S. Salinity Laboratory Staff 1954). Organic carbon was determined with the Walkley–Black wet oxidation procedure (Allison 1965) and multiplied by 1·72 to obtain organic matter content. Specific surface area was determined using ethylene glycol monoethyl ether (EGME) (Carter *et al.* 1965).

Infiltration, runoff and erosion were studied using a drip-type rainfall simulator. The simulator consisted of a 750 by 600 by 80 mm closed water chamber which generated rainfall of a known constant drop size through a set of hypodermic needles (approximately 1000) arranged at spacings of 20 by 20 mm and facing the ground. The average droplet diameter was $2{\cdot}97 \pm 5 \times 10^{-2}$ mm. The kinetic energy of the raindrops was varied by changing the height of fall of the droplets (i.e., the height of the chamber). Heights of 0·4, 1·0 and 1·6 m were used to obtain drops with impact velocities of 2·5, 4·02 and 4·98 m s^{-1}, respectively (Epema and Riezebos 1983). The corresponding kinetic energies were 3·6, 8·0 and 12·4 J mm^{-1} mm^{-2}, respectively. Rain rate was maintained at 33 mm h^{-1} using a peristaltic pump.

Table 1. Some physical and chemical properties of the soils used

Dominant clay minerals[A]	Specific surface area (m^2 g^{-1})	Particle size Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	CEC (cmol(+) kg^{-1})	ESP (%)	OM (%)
		Typic Chromoxerert[B] *(Site: Negba)*						
St, I	280	36·0	24·0	40·0	25·1	28·5	5·2	0·98
		Typic Rhodoxeralf (Site: Morasha)						
St, K	80	77·0	5·0	18·0	0·1	11·0	4·4	0·45
		Calcic Haploxeralf (Site: Bet Qama)						
St, I	120	50·0	31·0	19·0	11·4	17·6	3·7	0·96

[A] I, illite; K, kaolinite; St, smectite.
[B] Classification according to Soil Taxonomy (Soil Survey Staff 1975).

Air-dried aggregates, crushed to pass through a 4·0 mm sieve, were packed in 200 by 400 mm trays, 20 mm deep, over a 5 mm thick layer of coarse sand. In the control, no amendments were added to the packed soil trays. In the PG treatment, powdered PG at a rate equivalent to 5 Mg ha^{-1} was spread over the surface of the soil packed in the trays prior to rain. In the combined application of PAM and PG (PAM+PG treatment), an anionic low charge (20% hydrolysis) with a high molecular weight (~10^7 g mol^{-1}) PAM was used at a rate equivalent to 20 kg ha^{-1}. The PAM solution at a concentration of 0·5 g L^{-1} was sprayed on the soil surface in two portions of 2·0 L m^{-2}, each separated by 1 h of drying, thereby ensuring the proper concentration of the polymer at the soil surface. The soil in the trays was then allowed to dry for 24 h before powdered PG was spread at a rate equivalent to 5 Mg ha^{-1}. Thereafter, the soil in the trays was exposed to rain. Three replicates were used for each treatment concurrently.

Following the various pretreatments, the trays were placed in the rainfall simulator at a slope of 15%, saturated with tap water and exposed to a distilled water rainstorm. During each storm, water infiltrating through the soil was collected in graduated cylinders placed underneath a special outlet at the bottom of the tray, and its volume was recorded as a function of time. Runoff water which had spilled over the lower end of the trays was collected continuously throughout the storm in buckets. At the end of each storm, the runoff water in the buckets was mixed thoroughly and a subsample of 0·5 L was dried using a water bath at 80°C. The weight of the eroded material was then determined and total soil loss from the entire storm was calculated. The infiltration data obtained from the rainfall simulator were analysed as described by Levy *et al.* (1988), using a nonlinear regression equation proposed by Morin and Benyamini (1977). Significance of difference values, among treatments for the infiltration and erosion parameters studied, were determined using Tukey's procedure for multiple range test (Steel and Torrie 1960).

Results and Discussion

The properties, listed in Table 1, of the soils used in the present study indicate that the soils are all predominantly smectitic with organic matter

(OM) <1% and moderate levels of exchangeable sodium percentage (ESP). The soils differ in their clay and silt content, specific surface area and per cent $CaCO_3$, all of which are properties expected to influence aggregate stability, infiltration rate and amount of soil erosion when exposed to rain.

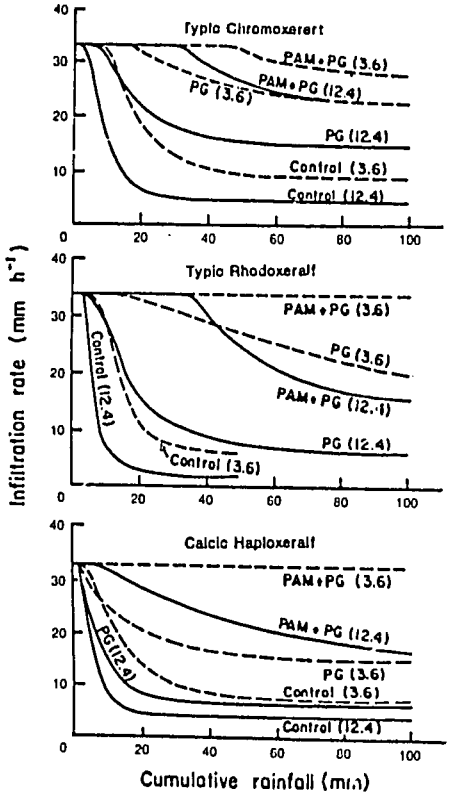

Fig. 1. Infiltration rates of the soils as a function of the cumulative rainfall (mm) at three kinetic energies (J mm^{-1} m^{-2}). Numerals in parentheses indicate the level of kinetic energy.

Infiltration

The calculated infiltration rate (IR) curves for the three soils and the various treatments are presented in Fig. 1. A coefficient of determination (R^2) between paired calculated and measured IR values was >95% in all treatments.

By considering, first, the IR curves of the control treatment for the three soils at the highest impact energy studied (12·4 J mm^{-1} m^{-2}), it is evident that the three soils contained unstable aggregates and were thus sensitive to seal formation. The IR curves dropped sharply and a rain depth of <30 mm was enough to form a seal with a final IR below 4·4 mm h^{-1} (Table 2). The soils studied were susceptible to sealing despite the fact that the impact energy tested was low and corresponds to the impact energy of low intensity natural

rain (Hudson 1973). These results support the conclusions of Ben-Hur *et al.* (1985) that cultivated smectitic soils from semi-arid regions have an unstable structure, resulting in poor infiltration and high levels of runoff when exposed to rain.

Table 2. Mean measured final infiltration rate (FIR) and depth of rain before ponding (DRP) obtained in the three soils at the three levels of raindrop energy

Within a column and for each soil, values followed by the same capital letter do not differ significantly at the 0·05 level. Within a row, values followed by the same lower case letter do not differ significantly at the 0·05 level

Raindrop energy (J mm^{-1} m^{-2})	Control FIR (mm h^{-1})	Control DRP (mm)	PG FIR (mm h^{-1})	PG DRP (mm)	PAM+PG FIR (mm h^{-1})	PAM+PG DRP (mm)
			Typic Chromoxeret			
3·6	8·9 A, c	10	21·8 A, b	18	27·3 A, a	48
8·0	5·0 B, c	4	12·3 B, b	8	14·4 C, a	26
12·4	4·4 B, c	4	14·6 B, b	8	22·0 B, a	34
			Typic Rhodoxeralf			
3·6	6·8 A, c	8	19·8 A, b	18	33·0 A, a	80
8·0	1·5 B, c	6	10·0 B, b	10	18·4 B, a	62
12·4	1·8 B, c	4	5·9 C, b	4	15·4 C, a	38
			Calcic Haploxeralf			
3·6	7·0 A, c	6	15·2 A, b	6	33·0 A, a	80
8·0	4·9 B, c	4	9·0 B, b	6	26·7 B, a	20
12·4	4·0 B, c	4	6·4 C, b	4	16·4 C, a	10

For the three soils, a decrease in raindrop energy from 12·4 to 3·6 J mm^{-1} m^{-2} resulted in (i) higher final infiltration rates (FIR) (Fig. 1), (ii) larger depths of rain to reach the point where the IR of the soil was equal to the rain intensity (i.e., depth of rain before ponding; Table 2), and (iii) larger cumulative depth of rain that infiltrated the soil (Fig. 2). Physical disintegration of the aggregates at the soil surface is one of the two mechanisms controlling seal formation (McIntyre 1958; Agassi *et al.* 1981). The rate and intensity of this mechanism depend strongly on the kinetic energy (KE) of the rain (Moldenhauer and Kemper 1969). Our results for the IR curve parameters show that, for the range of KE studied, the physical disintegration of aggregates determines the rate of seal formation and its final permeability. Consequently, upon increasing the energy of the raindrops, depth of rain to ponding (which is a measure of the rate of seal formation) became smaller and FIR decreased. The IR curves obtained at the intermediate raindrop energy level (8 J mm^{-1} m^{-2}) were either similar or close to the corresponding values obtained with the high KE raindrops (Table 2). It could be generalized that water drops with KE of 8 J mm^{-1} m^{-2} are destructive enough to form a fully developed seal at the soil surface for the soils studied.

Compared with the non-treated samples, the addition of PG to the three soils resulted in higher FIR values, generally larger depth of rain before ponding (Table 2), and larger cumulative infiltration values (Fig. 2). The effect of PG was more pronounced at the low energy rain and decreased as the impact energy increased, especially in the Typic Rhodoxeralf and Calcic Haploxeralf. In the

36

low energy rain, PG increased the FIR, compared with the control, by 13·0 and 8·2 mm h^{-1} in the Typic Rhodoxeralf and Calcic Haploxeralf, respectively. In the high energy rain, the corresponding differences in FIR were 4·1 and 2·4 mm h^{-1} in the Typic Rhodoxeralf and Calcic haploxeralf, respectively. By spreading PG on the soil surface, the electrolyte concentration at the surface soil solution is high enough to control the chemical dispersion mechanism and a more permeable seal is formed (Agassi *et al.* 1986). Our results show that the beneficial effect of PG is more pronounced under conditions where the mechanism for physical disintegration of aggregates is small, e.g., when the impact energy of the drops is low.

In all three soils, the combined treatment of PAM+PG maintained the highest FIR values and depths of rain before ponding (Fig. 1, Table 2). It is evident that the PAM+PG treatment was effective in improving aggregate stability and resistance to the beating impact of the raindrops, and hence in controlling seal formation. When PAM only was added to the soil, it had no beneficial effect on the structural strength of the soil (Shainberg *et al.* 1990; Smith *et al.* 1990). Shainberg *et al.* (1990) suggested that, in order for PAM to be an efficient soil conditioner, the soil clay must be in a flocculated form. Hence, the electrolyte concentration in the soil solution must exceed that of the flocculation value of the clay present in the soil. The PG, which provides an electrolyte concentration of ~10 mmol(+) L^{-1} to the soil solution, makes it possible for the PAM to act as a soil stabilizer. Furthermore, by keeping the soil clay flocculated, PG also limits the chemical clay dispersion that takes place during rainstorms, and reduces seal formation. The combined

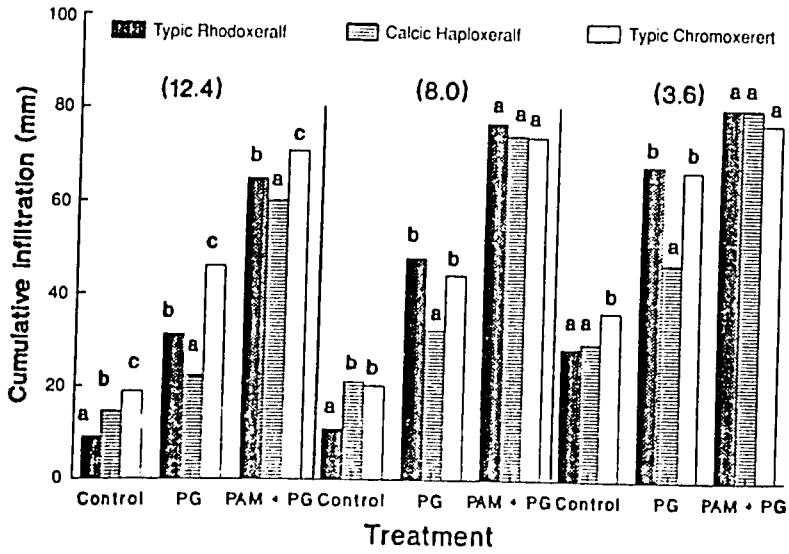

Fig. 2. Cumulative infiltration (for a 80 mm storm) for the various treatments, soils and kinetic energies (J mm^{-1} m^{-2}). Numerals in parentheses indicate the level of kinetic energy. Within treatments and levels of kinetic energy, bars labelled with the same letter do not differ significantly at the 5% level.

treatment of PAM and PG is thus very effective in controlling seal formation and improving IR because it restricts both mechanisms responsible for seal formation, namely (i) physical disintegration of the surface aggregates, and (ii) the chemical dispersion.

Soil Properties and Infiltration

Calculated infiltration values after 80 mm of rain are presented in Fig. 2. Cumulative infiltration is an integrated value that reflects the rate at which the seal is formed and its final permeability. The results for the control treatment show that cumulative infiltration (Fig. 2), and the measured FIR values (Table 2) in the Typic Chromoxerert were generally higher than, or comparable with, those of the Typic Rhodoxeralf and of the Calcic Haploxeralf. The cumulative infiltration of the noncalcareous Typic Rhodoxeralf was the lowest (Fig. 2), indicating that this soil is the most susceptible of the three soils to sealing. It is suggested that the Typic Chromoxerert and the Calcic Haploxeralf are less susceptible to sealing because these soils are calcareous, and hence during the rain event probably released some electrolytes to the soil solution by $CaCO_3$ dissolution and thus clay dispersion was inhibited. The higher clay content and lower silt content in the Typic Chromoxerert compared with the Calcic Haploxeralf (Table 1) might explain the higher FIR values in the Typic Chromoxerert. Wet sieving studies showed that aggregate stability was positively correlated with clay content (Kemper and Koch 1966), whereas high silt content was associated with low structural stability (Cary and Evans 1974).

In the PG and PAM+PG treatments, chemical dispersion of the clay is controlled by the dissolved PG, and the physical breakdown of aggregates is the predominant factor in governing seal formation. In these two treatments, the FIR values of the Typic Rhodoxeralf and the Calcic Haploxeralf were comparable. However, the cumulative infiltration values of the Typic Rhodoxeralf were higher than, and similar to, the Calcic Haploxeralf in the PG and the PAM+PG treatments, respectively. This suggests that, in the PG treatment, the PG dissolution masked the difference in the sensitivity of the two soils to clay dispersion. Thus, the cumulative infiltration values in the Typic Rhodoxeralf were higher than those in the Calcic Haploxeralf because its silt content is only 5%, compared with 31% in the Calcic Haploxeralf (Table 1). In the PAM+PG treatment, the contribution of the PAM to aggregate stability is the reason for the similar susceptibility to seal formation in both soils as reflected by their similar FIR and cumulative infiltration values.

Table 3. The ratio between cumulative infiltration data obtained from the soil-amended treatments and those obtained from the control

Soil	Raindrop energy (J mm^{-1} m^{-2})	Soil amendment PG	Soil amendment PAM+PG
Typic Chromoxerert	3·6	1·8	2·1
	12·4	2·4	3·7
Calcic Haploxeralf	3·6	1·6	2·7
	12·4	1·5	4·1
Typic Rhodoxeralf	3·6	2·4	2·8
	12·4	3·4	7·1

38

The combined effects of soil type and soil amendments (e.g. PG and PAM+PG) at the lowest and highest KE of raindrops studied are summarized in Table 3, where values are given for the ratio between cumulative infiltration obtained in the treatments where soil amendments were used, and cumulative infiltration obtained in the control. From Table 3, it is noted that:

(i) The effect of PG and PAM+PG in increasing cumulative infiltration was generally similar at the low KE (with the exception of the Calcic Haploxeralf), but at the higher KE the effect of PAM+PG was greater than that of PG alone. When rain with low KE is used, the relative importance of clay dispersion in sealing is enhanced and aggregate disintegration is less important. The presence of PAM, which increases aggregate strength, was less pronounced in the low KE rain and the effect of PG predominated. Thus, the two treatments (PG and PAM+PG) had a similar effect in increasing cumulative infiltration in the low KE rain. When raindrops with high KE were used, prevention of aggregate breakdown by the beating impact of the drops became essential. Treatment of the soil with a soil-stabilizing agent (PAM) in addition to a source of electrolytes (PG) was much better than PG alone in preventing seal formation.

(ii) The beneficial effect of the soil amendments varied between soils at KE of $12 \cdot 4\ J\ mm^{-1}\ m^{-2}$. In the PAM+PG treatment, cumulative infiltration in the Typic Chromoxerert increased to $3 \cdot 7$ times that of the control compared with $7 \cdot 1$ times in the Typic Rhodoxeralf. Thus, the higher initial stability of the soil, the smaller the relative effectiveness of the soil amendments in preventing seal formation.

Soil Erosion

Soil losses from 80 mm rainstorms are presented in Fig. 3. The results show that (i) soil loss increased with an increase in rain KE, and (ii) the greatest amount of soil loss was observed in the control and the lowest in the PAM+PG treatment, with that in the PG treatment being intermediate. The beneficial effect of PAM+PG and PG treatments in reducing soil erosion occurred not only because cumulative infiltration increased and therefore runoff decreased, but also because soil particles at the surface were larger than those in the untreated soil, and hence, (i) more difficult to detach, and (ii) quicker sedimentation of the suspended particles occurred (Agassi *et al.* 1989).

A comparison of the erodibility of the three soils in the control treatment shows that the Typic Rhodoxeralf was the most erodible. The high soil loss from this soil with all KE treatments is associated with the high runoff levels observed in this soil. The higher ESP and the absence of $CaCO_3$ in this soil compared with the Typic Chromoxerert account for the its high erodibility. With the exception of the PAM+PG treatment, soil losses from the Typic Chromoxerert were in general significantly smaller than those from the two other soils used. This observation is in agreement with the infiltration parameters (i.e., FIR and cumulative infiltration) discussed previously. On the other hand, in the PAM+PG treatment, soil losses from the three soils did not differ significantly at any level of rain KE (Fig. 3), although differences were observed in the infiltration parameters (Figs 1 and 2, Table 2). These

-39

conflicting results with respect to the link between infiltration parameters and soil erosion suggest that it is possible that infiltration parameters and soil erosion are not always directly related and it would therefore be unsound to predict soil erosion from the infiltration parameters.

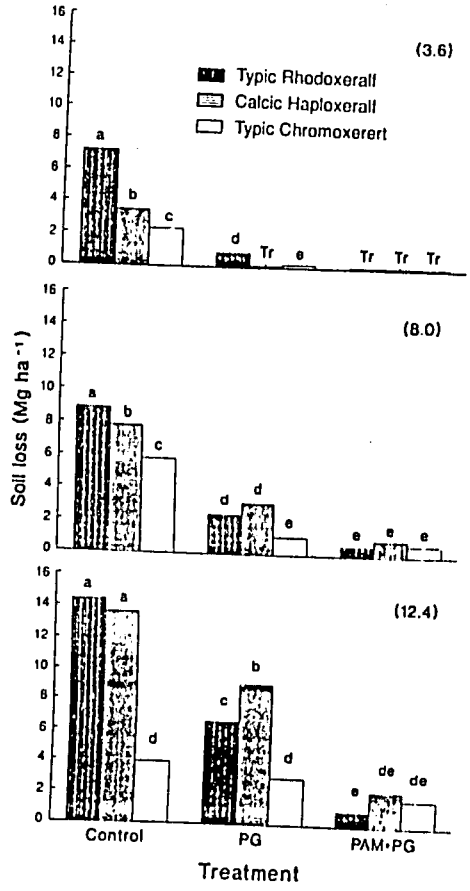

Fig. 3. Total soil loss after 80 mm storms from the three soils for the different treatments and rain kinetic energies (J mm^{-1} m^{-2}). Numerals in parentheses indicate the level of rain kinetic energy. Bars labelled with the same letter do not differ significantly at the 5% level (Tr, trace).

Conclusions

The infiltration parameters (i.e., FIR, depth of rain to ponding and cumulative infiltration) of the nontreated soils studied were affected by the KE of the raindrops. An increase in the KE was followed by a decrease in the infiltration parameters. Addition of PG and PAM+PG resulted in higher infiltration

40

parameters and hence limited seal formation. However, the effect of PG was more pronounced in the low KE rains because in the PG treatment only the chemical clay dispersion process, which carries more weight in seal formation at low KE rain, was prevented. The effect of PAM+PG in controlling seal formation increased with an increase in rain KE. This was so because, in addition to the effect of PG, the PAM limited the physical disintegration of the aggregates caused by the beating impact of the raindrops; the latter being a process where the PAM effect increases with increasing KE of the rain. The Typic Chromoxerert was the least susceptible of the three soils to sealing, probably because of its high clay and $CaCO_3$ contents which enhance soil stability. The Typic Rhodoxeralf and the Calcic Haploxeralf contain similar amounts of clay (approx. 19%), yet they differed in their susceptibility to the two mechanisms controlling seal formation. The noncalcareous Typic Rhodoxeralf was especially sensitive to clay dispersion, whereas the Calcic Haploxeralf, because of its high silt content, was sensitive mainly to the impact energy of the raindrops. The effects of rain KE and soil amendments on soil erosion were similar in the three soils to those observed from the infiltration parameters, with the exception of the PAM+PG treatment. This exception suggests the possibility that infiltration parameters and soil erosion are not necessarily directly related.

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41

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42

Appendix 5

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Slope, Aspect, and Phosphogypsum Effects on Runoff and Erosion

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44

Soil amendments and mulch effects on runoff and erosion - laboratory study

Experimental

Three soils with a sandy loam texture, collected from regions with winter precipitation exceeding 350 mm were used for this study. Some physical and chemical properties of the soils are given in Table 1.

Runoff and erosion were studied using a drip-type rain simulator. The rain simulator was constructed of a closed water chamber placed 2.8 m above the soil samples. Rain was generated through hypodermic needles to form a known droplet size. Average water drop diameter was 3.2 mm, impact velocity was 6.3 m s^{-1} and rain kinetic energy was 19.8 J mm^{-1} m^{-2}. Rain intensity was maintained at ~77.3 mm h^{-1}.

Soil samples with aggregates <4 mm, were packed in 200 X 600 mm boxes to a depth of 30 mm over 50 mm of coarse sand. The three soils were packed similarly with bulk density of 1.50, 1.27 and 1.45 for the Alvalade (Al), Mitra (Pg) and Vale Formoso (Vx) soils, respectively.

Two sets of experiments were carried out. In the first the treatments studied were a control, phosphogypsum (PG) spread over the soil surface at the equivalent rate of 5 ton ha^{-1} and wheat straw

45

mulch at the rate of 3 ton ha^{-1}. In the second one, the effect of an anionic low charge with high molecular weight polyacrylamide (PAM) on controlling runoff and erosion was studied. Prior to rainfall simulations the packed soil containers were treated as follows:

I. C (control) - the soil was saturated and allowed to drain for 24 h.

II. P1000 - PAM was added to the soil surface at an equivalent rate of 10 kg ha^{-1} by spraying a solution containing 1000 g m^{-3} of the polymer. Thereafter the soil was allowed to dry at 30°c and then it was saturated and again was allowed to drain for 24 h.

III. P1000G - similar to treatment II but with application of 5 ton ha^{-1} of PG prior to saturation.

IV. P100 - similar to treatment II but using a 100 g m^{-3} PAM solution.

V. P50 - similar to treatment II but using a 50 g m^{-3} PAM solution.

VI. P50G - similar to treatment II but using a 50 g m^{-3} PAM solution.

Treatments IV, V, and VI were studied with the Alvalade soil only. Three and four replicates were performed for each treatment in the first and second set of experiments, respectively.

After the various pretreatments, the containers were placed a 3% slope under the rain chamber and exposed to distilled water rain of 45 and 77 mm in the first and second set of experiments, respectively. Infiltration and runoff were recorded every 5

minutes. Sediments, detached by splash and transported by wash, were collected every 5 minutes in the first set of experiments and continuously throughout the rainfall event in the second set.

Results

The erosion collected from the soil boxes and calculated infiltration rate (IR) as a function of cumulative time during rain event for the three soils in the first set of experiments are presented in Figures 1, 2, 3 and 4. With respect to their susceptibility to erosion the soils can be arranged in the following descending order: Alvalade (Al)> Vale Formoso (Vx)> Mitra (Pg)(Figs. 1 and 2). For all three soils, soil erosion and IR in the mulched treatment were always significantly lower and higher, respectively, than those in the other two treatments. No difference was observed between the PG and the control treatments in both parameters.

The infiltration curves for the various soils and treatments obtained at the second experiment are presented in Figs. 5-8. Generally, the PAM treatments were effective in increasing the infiltration rate (IR) as compared with the control. The favorable effect of P1000 and P1000G treatments on the IR of the three soils was in the following decreasing order: Mitra>Alvalade>Vale Formoso. Supplementing the PAM by PG application did not significantly improve the IR of the Alvalade and Vale Formoso soils as compared to the PAM only treatment (Figs. 5 and 7). In the Mitra soil, the P1000G treatment caused a sig-

47'

nificant and marked increase in the IR as compared to the P1000 and control treatments (Fig. 6). In the cases where PAM was added using low concentration solutions (treatments IV, V and VI), the P100 treatment was the most effective in maintaining high IR that was three times higher than that of the control (Fig. 8). The IR obtained in the P100 was also higher than the IR obtained in the P1000 and P1000G treatments (Figs. 8 and 5, respectively).

The amount of total (detached and washed) sediments (i.e., eroded soil) removed form the three soils under the various experimental conditions are presented in Fig. 9. The P1000 was the only treatment that reduced the amount of sediments removed as compared with the control. The highest amount of sediments removed was observed in the P100 treatment. Addition of PG resulted in higher amounts of sediments as compared to the equivalent PAM only treatments. Among the various concentrations of PAM solution tested in the Alvalade soil, the 1000 g m^{-3} concentration (with and without PG) resulted in significantly lower amounts of sediments.

Discussion

PG was expected to prevent the chemical clay dispersion during the rain event and consequently to improve the IR and reduce soil erosion. The results of the first set of experiments indicate that in the soils studied clay dispersion was not an important factor in determining the IR of the soil and in the controlling of soil erosion. Preventing the physical disintegration of the

-48

surface aggregates by the impact energy of the raindrops, on the other hand, as was the case in the mulch treatment, was very effective in maintaining high IR values and low amounts of eroded material.

Another possibility to control the IR is to increase the stability of the aggregates at the soil surface. This can be achieved by adding low quantities of soil conditioner like PAM to the soil surface. The results of the second set of experiments indicated that this treatment was effective in maintaining high IR. However, it was noted that for both high (P1000 and P1000G), and low (P100, P50 and P50G) PAM concentrations high IR is coupled with high amounts of sediments. Thus the ranking for the IR and amount of sediments is in the following decreasing order for the two groups respectively, P1000>P1000G and P100>P50G>P50. This phenomenon of high IR coupled with high amounts of sediments was contradictory to that observed in the first set of experiments where high IR was coupled with low amounts of soil loss.

The changes in the IR during rainfall are an indication of the rate of seal formation and the ratio between the amount of water penetrating the soil and runoff water. It is not clear how the development of the seal affects soil erosion. Seal formation increases the shear strength of the soil surface which reduces soil detachment. However, the seal formed also reduces infiltration and hence increases runoff which increases detachment and sediment transport by surface flow (Bradford et al., 1987). The relative importance of the detachment and transport processes depend

49

on the experimental conditions. Differences in the experimental procedure between the two sets of experiments, especially in the method of sediment collection and the duration of the rain storms could account for the aforementioned discrepancy.

Figure legend

Figs. 1 and 2: Soil loss measured in the rainfall simulator as a function of rainfall duration for the three soils.

Figs. 3 and 4: Calculated IR from simulated rainfall studies as a function of simulated rainfall duration for the three soils.

Figs. 5 to 8: Infiltration rate from simulated rainfall as a function of cumulative rain for the three soils and various treatments.

Fig. 9: Total sediment removed during the rainstorm for the soils and treatments.

50

A distrometer was installed in March 91 and the data obtained since will be used to verify the calibration.

Figure legend

Fig. 1: Rain intensity vs. rain duration for a recurrence interval of 2 years.

Fig. 2: Cumulative precipitation vs. rainfall duration.

Fig. 3: Measured soil loss for crop sequence of A-T (plots 1, 2, 10 and 11).

Fig. 4: Measured soil loss for crop sequence of A-T (plots 7 and 7x).

Fig. 5: Measured soil loss for crop sequence of A-T-S-P-P (plots 8, 9, 12, 13, 14 and 15).

Fig. 6: Measured soil loss for crop sequence of T-S-T (plots 3, 4, 5 and 6).

Fig. 7: Measured soil loss for crop sequence of T-S-T-G (plots 8, 9, 12 and 13).

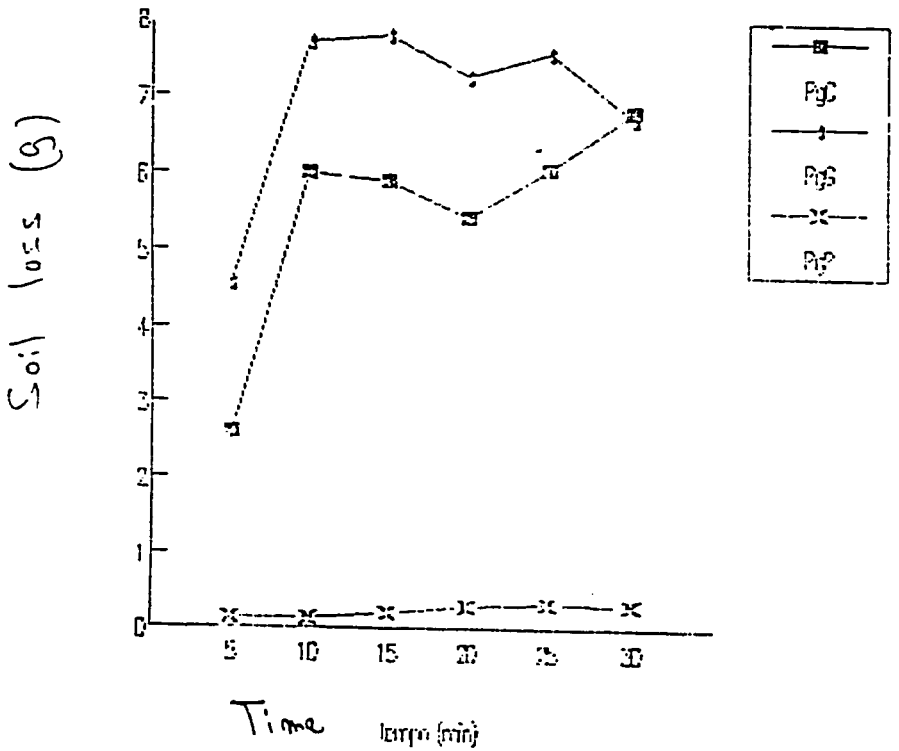
51

Table 1: Some physical and chemical properties of the soils studied.

Soil		Clay mineralogy*	Particle size distribution				CEC	pH	OM
Location	Classification		coarse sand	fine sand	silt	clay			
			%				$cmol_c\ kg^{-1}$		%
Mitra (Pg)	Haploxeralf (derived from Granite)	K (35-45%) M (35-45%) Ist (10-20%)	46.1	33.1	13.8	7.0	5.2	5.9	0.8
Vale Formoso (Vx)	Rhodoxeralf (derived from Shist)	K (40-50%) M (40-50%) V (< 5%)	30.5	27.5	30.7	11.3	4.9	5.8	0.8
Alvalade (Al)	Aluvial	K (50-60%) M (35-45%) V (< 1%)	8.1	43.7	30.8	17.4	10.0	6.9	0.8

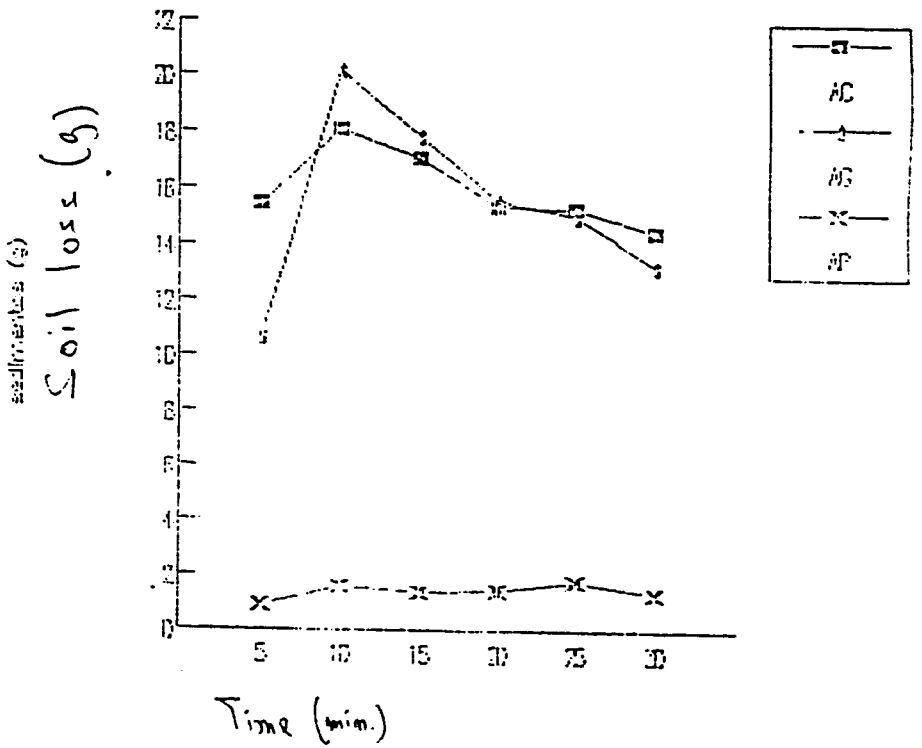
*Ist = Intrastratified material. K = Kaolinite, M = Mica, V = Vermiculite

Mitra



PgC - Control
PgG - Gypsum
PgP - Straw

Alvalade



AC - Control
AG - Gypsum
AP - Straw

Fig. 1

Vale Formose

V x C - Control

V x G - Gypsum

V x P - Straw

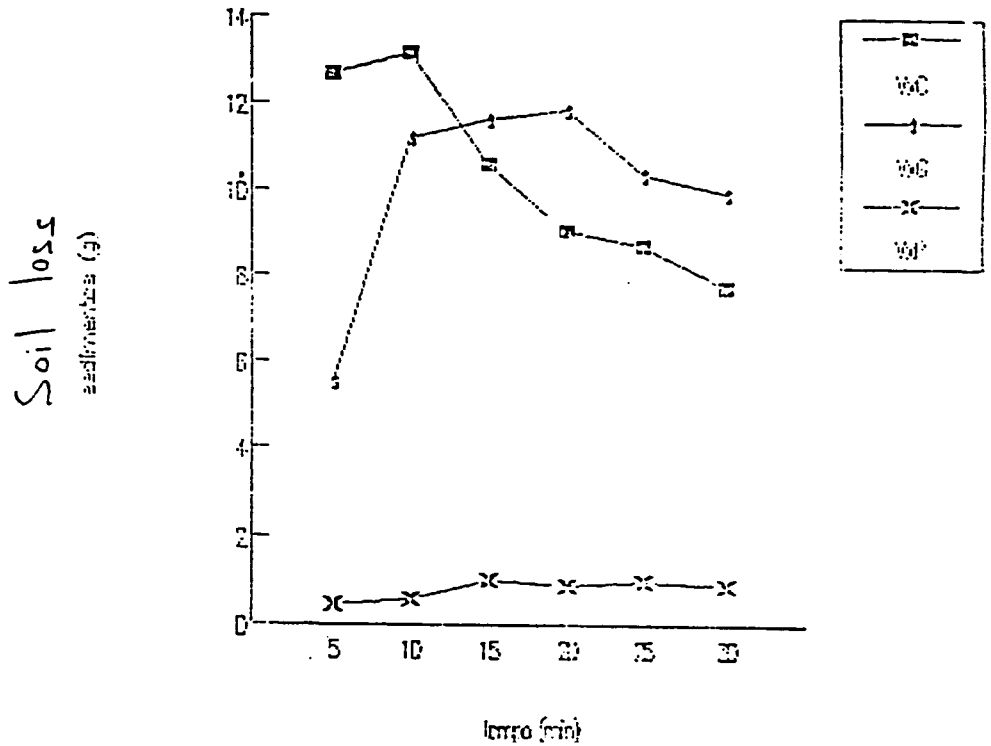


Fig. 2

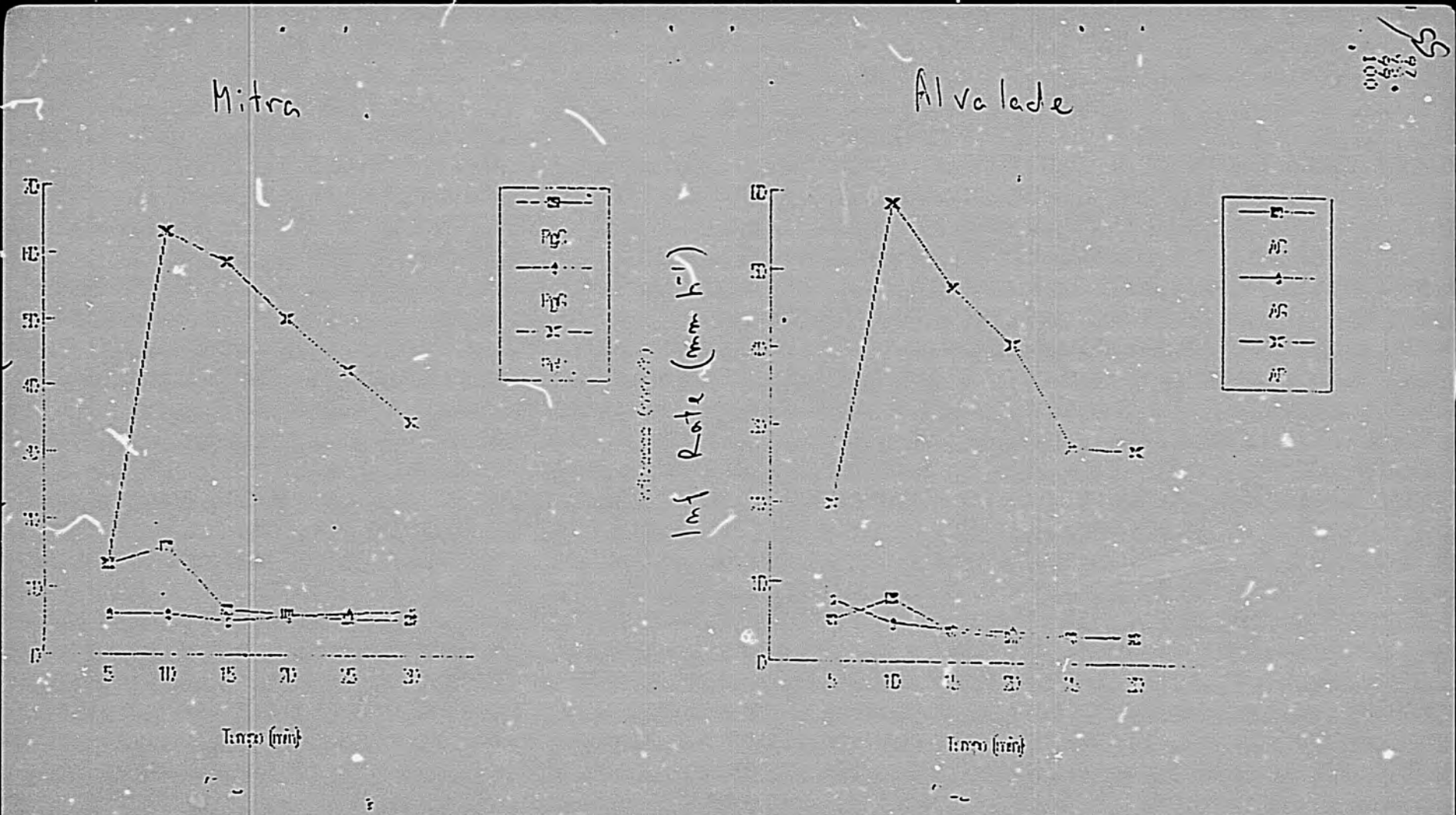
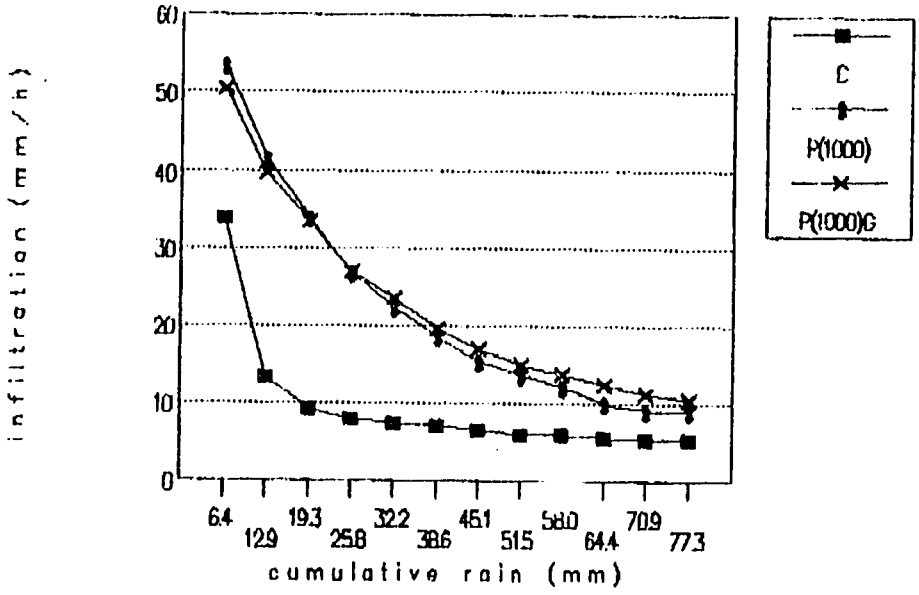

Mitra
Alvalade
Inf Rate (mm h-1)
Tempo (min)
Tempo (min)
PgC
PgG
AC
AG
AP

Fig. 3

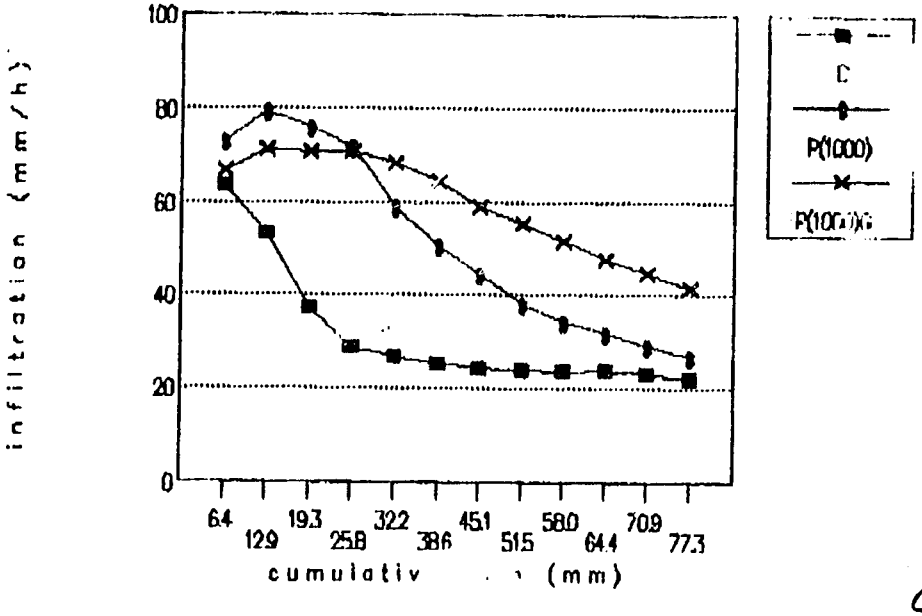
Vale - Formosa

Fig. 4

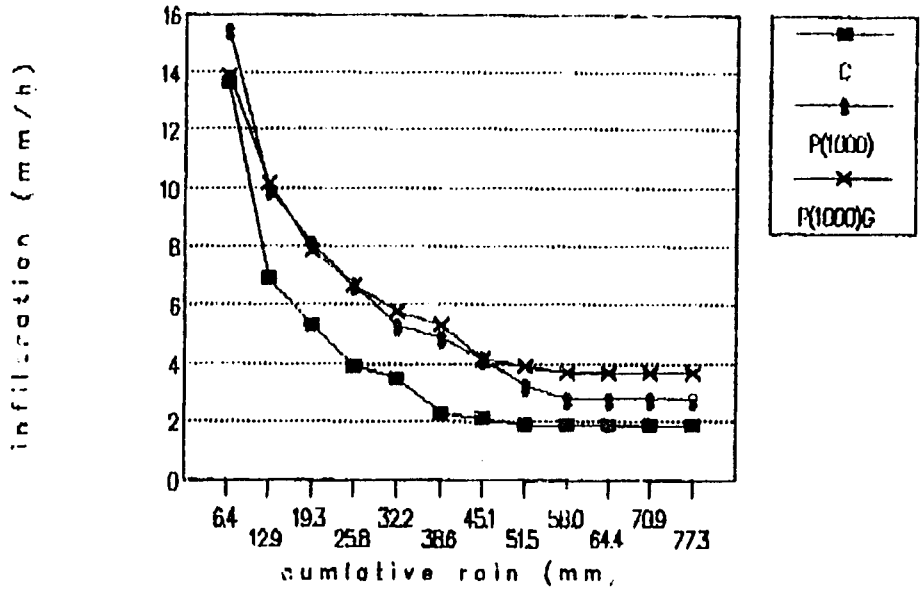
A SOIL



Pg SOIL

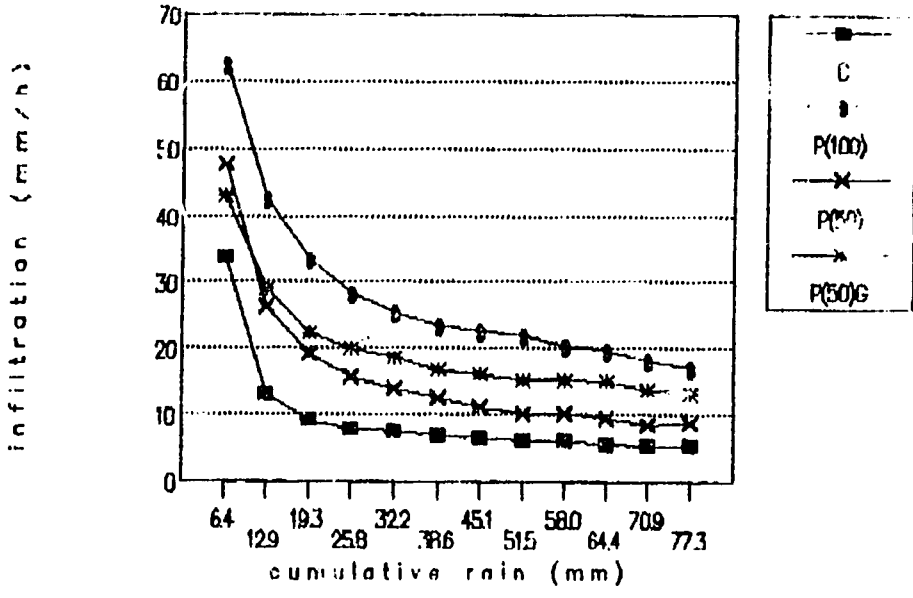


Vx SOIL



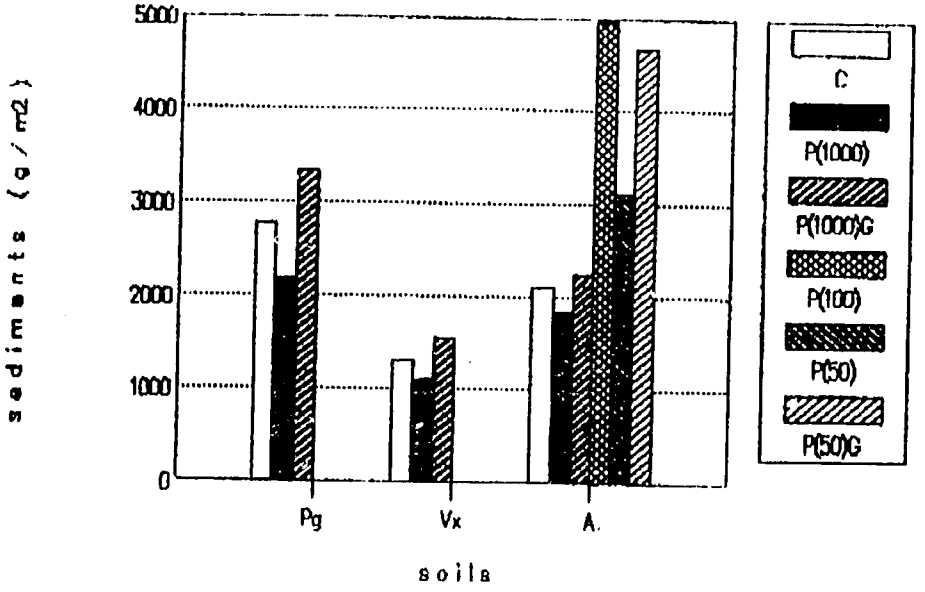
Fig

A SOIL



Fig

TOTAL OF SEDIMENTS



Appendix 9

Soil amendments and mulch effects on runoff and erosion under natural rain conditions.

Experimental

Runoff and erosion were collected during the winters of 1988/89 and 1989/90, and erosion in the winter of 1990/91 from 2 m (2x1 m) plots located where the soils used in the laboratory studies (see Appendix 8) were sampled. The slopes of the plots in the three sites were similar to the natural slope existing in the field which were 4, 9 and 0.5% in the Mitra, Vale Formoso and Alvalade sites, respectively. Two sets of treatments were studied. In the winters of 1988/89 and 1989/90 the treatments studied were similar to those used in the first set of the laboratory experiments and included a control, PG and mulching by straw. In the winter of 1990/91 the following treatments were studied: (i) bare soil (alqueive), (ii) PG at a rate of 5 ton ha^{-1} (gesso), and (iii) PAM at a rate of 20 kg ha^{-1} together with PG at a rate of 5 ton ha^{-1} (PAM+PG).

Results

Cumulative runoff as a function of rain events for the winters of 1988/89 and 1989/90 is presented in Figs. 1-6. In general, runoff levels in the 89/90 season were higher than those in the previous year because precipitation in the winter of 89/90 was higher than that in the winter of 88/89 (Table 1). More specifically, the

following should be noted:

1) In the Mitra and Alvalade soils (Figs. 1-4), runoff levels were similar in the control and PG treatments and somewhat lower in the mulched soil. In the Vale Formoso soil the amount of runoff in the PG was ~25% lower than those observed in the other two treatments (Figs. 5 and 6).

2) In the Alvalade soil, percent runoff out of annual precipitation in the control treatment was higher in the 88/89 winter compared with the 89/90 winter although precipitation in the latter winter was significantly higher than that in the former one (Table 1). It is common knowledge that the higher the annual precipitation the lower the average rain intensity and in turn rain kinetic energy. Hence, following the lower average kinetic energy of the rain in the 89/90 winter a more permeable seal was formed in this soil resulting in a lower amount of runoff.

3) In the Vale Formoso and Mitra soils higher percent of runoff was observed in the 89/90 winter than in the previous one (Table 1). In the Mitra soil as much as 58% runoff was obtained in the second winter compared with only 15% in the first one. The reason for the drastic increase in runoff is probably associated with the fact that the this soil is very shallow, only 450 mm deep, lying over an impermeable rock. Thus perched water table was formed in this soil during the rainy winter of 89/90. The high amounts of runoff observed in this soil did not result therefore from poor permeability because of seal formation but because water could not enter the already saturated

62

soil profile.

Cumulative amounts of erosion as a function of rain events for the three soils and the various treatments are presented in Figs. 7-12. For all three soils and for both years, erosion levels in the mulched treatment were lower than those obtained in the other two treatments despite the similarity in the runoff levels among the three treatments (Table 1). The mulch protected the soil from the beating impact of the raindrops and prevented detachment of particles at the soil surface and their transfer to the runoff water. In addition, the rate of flow of the runoff water which is its main source of power for detaching soil particles was limited due to its tortuous flow induced by the mulch.

The effect of PG on erosion differed in all three soils. In the Mitra soil PG was effective in reducing soil erosion in the 89/90 winter, however in the former winter similar amounts of erosion were observed in the control and PG treatments (Figs. 7 and 8 & Table 1). In the Vale Formoso the effectiveness of PG in reducing erosion was observed in the 88/89 while in the following year similar amounts of erosion were obtained in the control and PG treatments (Figs. 9 and 10). In the Alvalade, higher amounts of eroded material were obtained in both years in the PG treatment compared with the control (Figs. 11 and 12).

Cumulative amounts of erosion as a function of rain events of winter 1990/91 for the three soils are presented in Figs. 13-15. The three soils responded differently to the various treatments.

In the Mitra soil, the PAM+PG and PG treatments increased soil loss by fourfold and twofold, respectively as compared with the control (Fig. 13). In the Vale Formoso soil, the PG decreased soil erosion and PAM+PG increased soil erosion as compared with the control (Fig. 14). The difference between the treatments were, however, small and insignificant. In the Alvalade soil, both PG and PAM+PG decreased soil erosion to approximately 60% of that of the control (Fig. 15). Reasonable agreement between laboratory and field results for the PAM+PG treatment were observed in the Vale formoso soil only (Figs. 9 and 15).

The results of the three years of field experiments support the results obtained in the laboratory with respect to the mulch. They indicated that the mulch was the preferable treatment for controlling runoff and erosion. Adding PG to the soil surface generally did not reduce runoff and erosion compared with the control. In some cases PG even enhanced soil erosion. The effect of PAM+PG was also not consistent and varied with the type of soil. It may be concluded that the beating impact of the raindrops and hence physical disintegration of the surface aggregates is the predominant mechanism in seal formation in the soils studied under conditions of natural rains. Chemical clay dispersion, on the other hand, plays apparently an insignificant role in the process of sealing. Consequently, in order to prevent seal formation and control runoff and soil erosion measures that improve soil stability and its resistance to the impact energy of the raindrops should be employed.

Figure legend

Figs. 1 to 6: Cumulative runoff vs. time (months) obtained in the winters of 1988/89 and 1989/90 for the various soils and treatments.

Figs. 7 to 12: Cumulative soil loss vs. time (months) obtained in the winters of 1988/89 and 1989/90 for the various soils and treatments.

Figs. 13-15: Cumulative soil loss vs. time (months) obtained in the winter of 1990/91 for the various soils and treatments.

65

Table 1: Crop rotation and some factors of the USLE for the erosion plots in Vale Formoso.

Plot	Years	Crop sequence	L	S	LS	P
			m	%		
1	1960/61-1985/86	Wheat (T) - Bare soil (A)	20.1	11.0	1.27	0.6
2			20.1	10.2	1.14	0.6
10			20.2	16.0	2.27	0.7
11			20.2	16.0	2.30	0.7
7	1966/67-1985/86	Wheat (T) - Bare soil (A)	20.2	12.9	1.63	0.7
7x			20.2	13.3	1.72	0.7
3	1969/70-1985/86	Wheat (T) - Barley (S)	20.1	9.8	1.07	0.6
4			20.1	9.6	1.04	0.6
5			20.1	10.5	1.18	0.6
6			20.1	12.0	1.44	0.6
8	1960/61-1967/68	Bare soil (A) - Wheat (T) -	20.2	14.9	2.04	0.7
9		- Barley (S) - Wheat -	20.2	15.5	2.18	0.7
12		- Pasture (P) - Pasture	20.3	16.5	2.42	0.8
13			20.3	17.6	2.67	0.8
14			20.4	20.1	3.34	0.8
15			20.4	20.3	3.39	0.8
8	1969/70-1985/86	Wheat (T) - Barley (S) -	20.2	14.9	2.04	0.7
9		- Wheat -	20.2	15.5	2.18	0.7
12		- Barley (G, grains)	20.3	16.5	2.42	0.8
13			20.3	17.6	2.67	0.8
14	1970/71-1985/86	Pasture (P)	20.4	20.1	3.34	0.8
15			20.4	20.3	3.39	0.8

Table 2: Mean measured and predicted soil losses for the various crop sequences.

Crop Sequence	Plot	Soil loss			
		Measured	SD*	Predicted (USLE)	SD
		ton ha^{-1}		ton ha^{-1}	
T-A	1,2	1.09	1.41	10.4	0.55
	10,11	0.63	0.82	22.9	0.11
	7,7x	0.30	0.42	16.8	0.45
T-S	3-6	0.48	0.57	8.9	1.19
A-T-S-P-P	8-15	0.58	0.39	18.6	4.50
T-S-T-G	8-13	0.47	0.62	20.7	3.41
P	14,15	0.33	0.52		

*One standard deviation.

Fig. 1

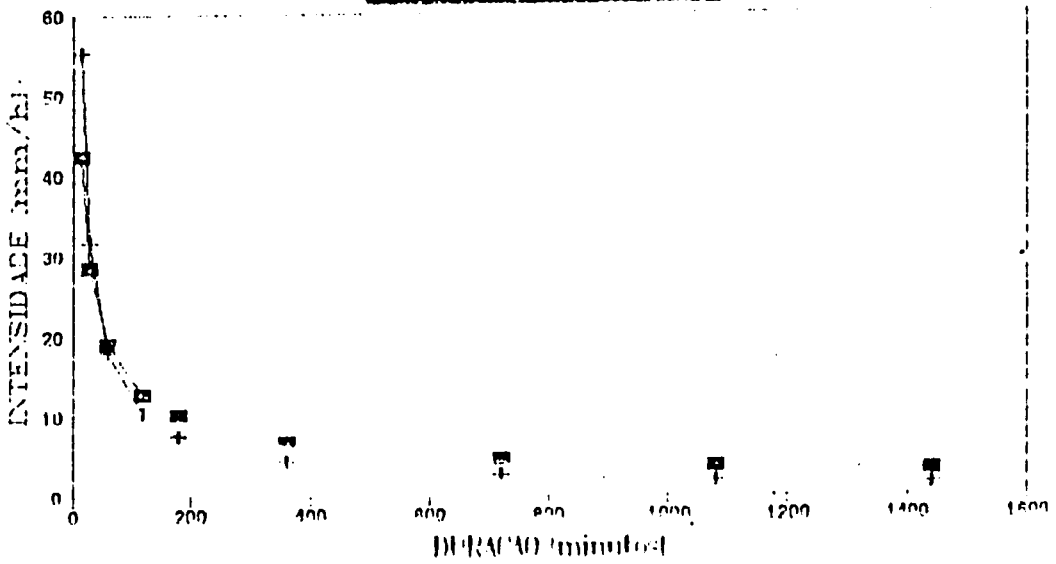
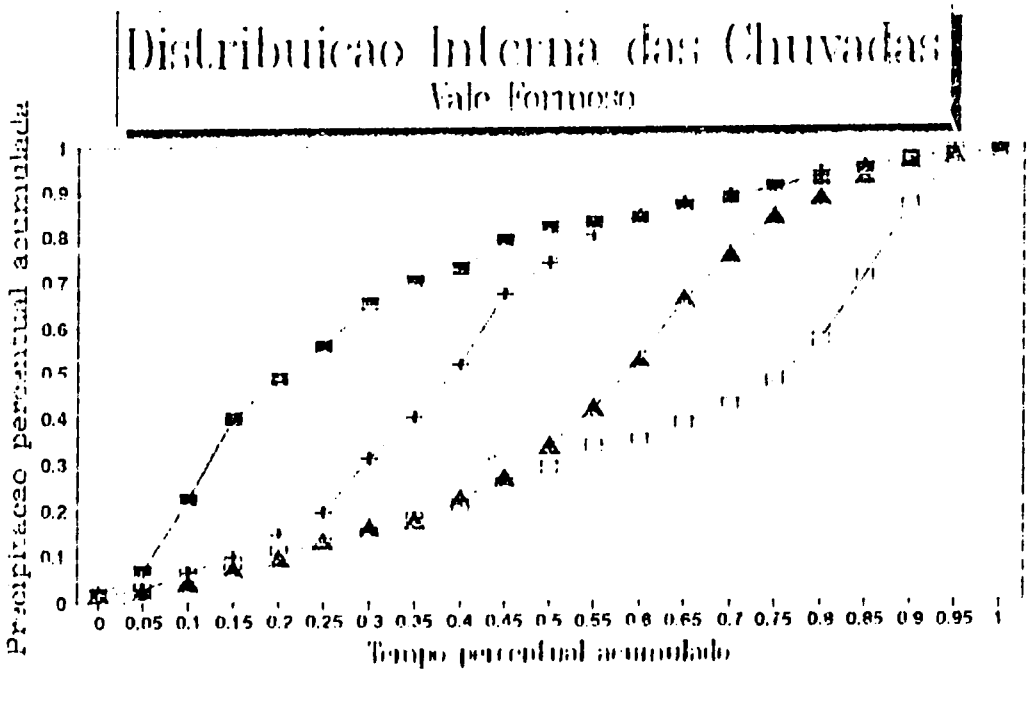


Fig. 2



168

Fig. 3

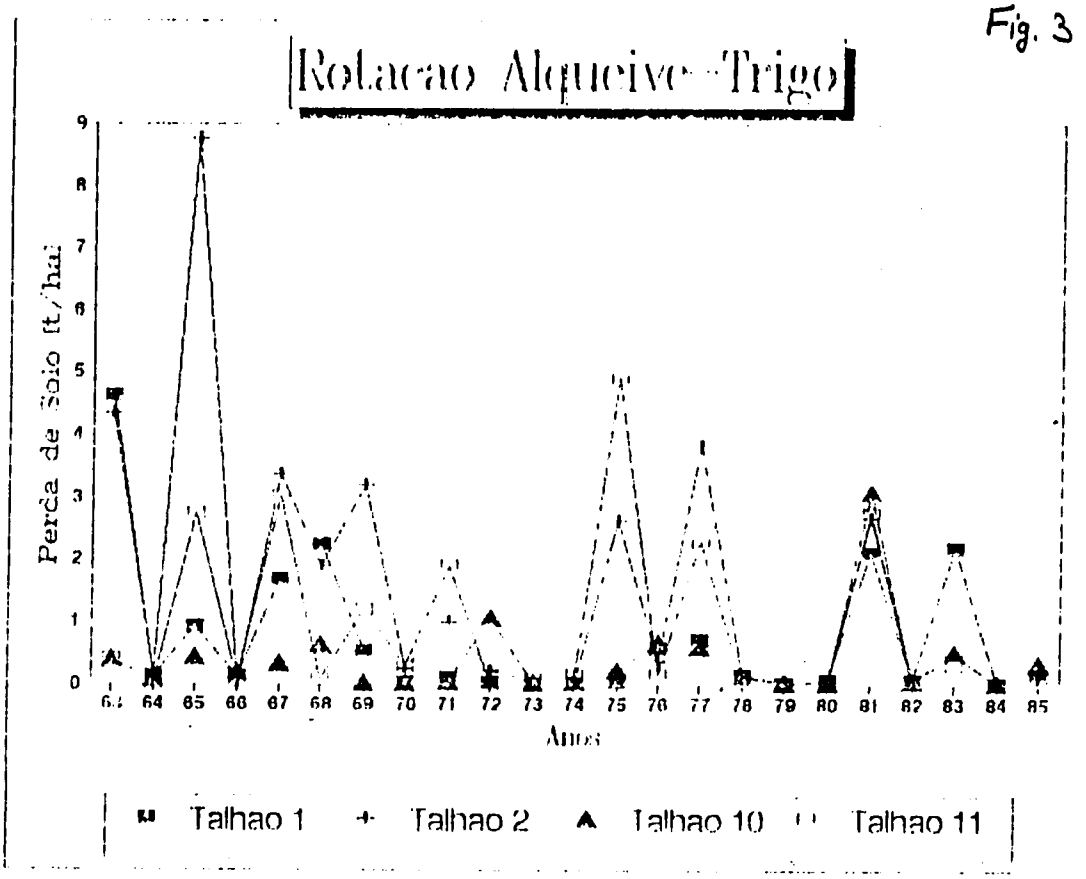

Rotacao Alqueive-Trigo
Perda de Solo (t/ha)
Anos
Talhao 1
Talhao 2
Talhao 10
Talhao 11

Fig. 4

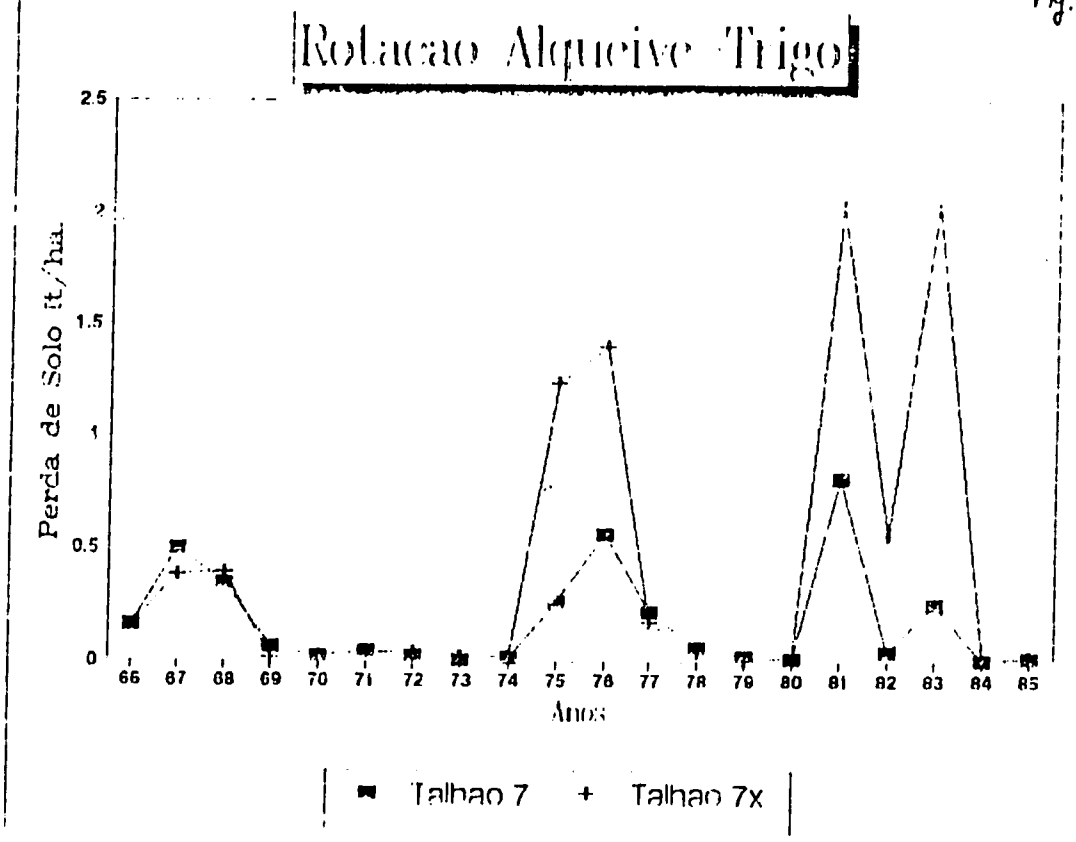

Rotacao Alqueive-Trigo
Perda de Solo (t/ha)
Anos
Talhao 7
Talhao 7x

Fig. 5

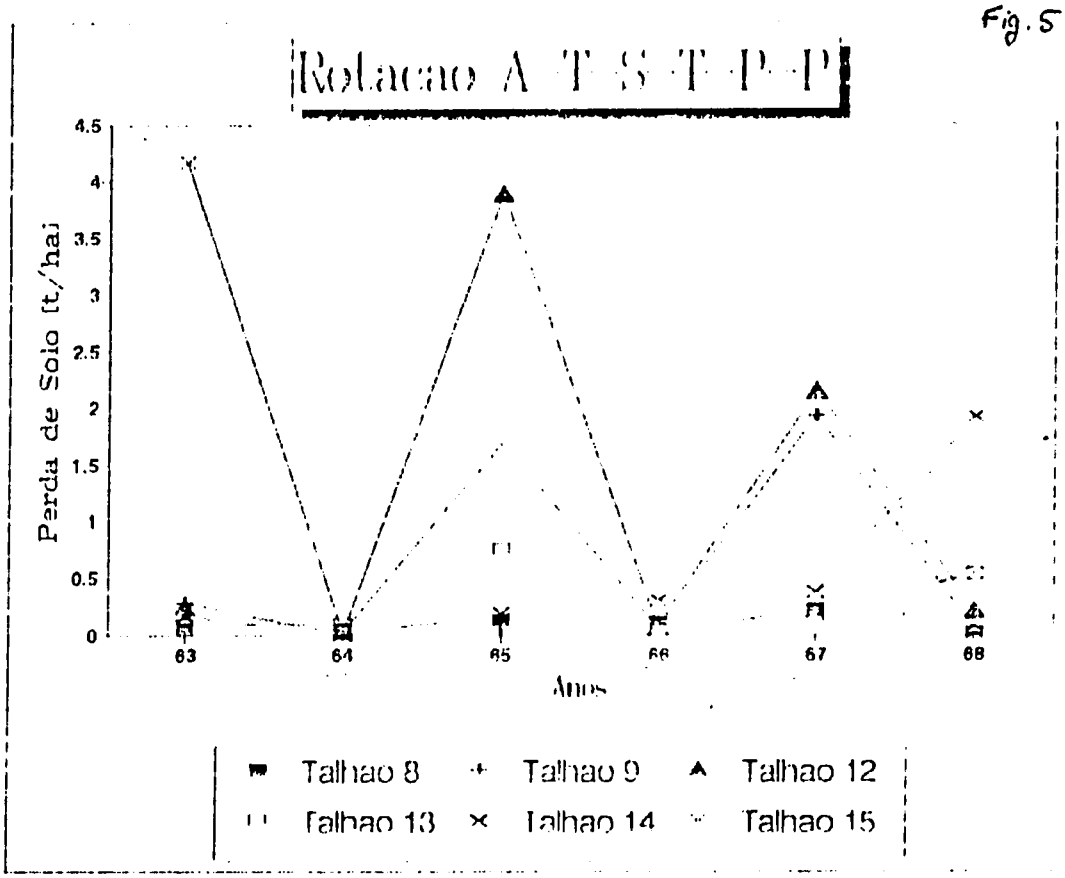
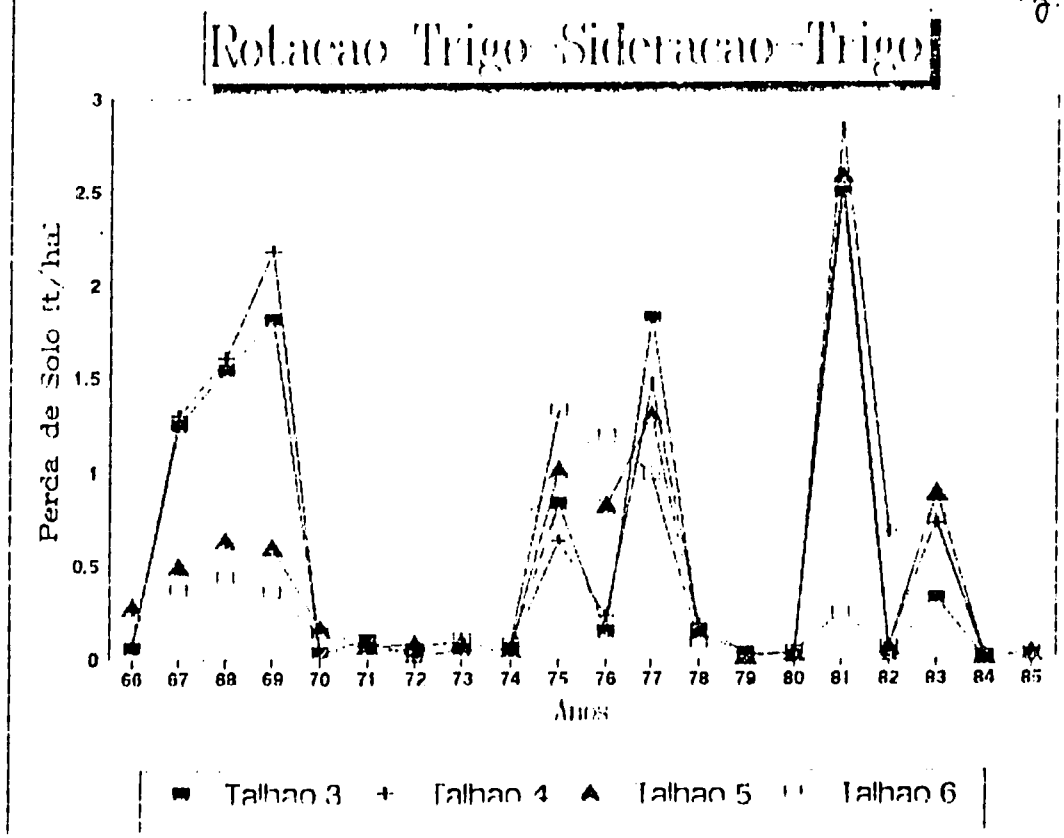

Rotacao A-T-S-T-P-P
Perda de Solo (t/ha)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
63
64
65
66
67
68
Anos
Talhao 8
Talhao 9
Talhao 12
Talhao 13
Talhao 14
Talhao 15

Fig. 6


Rotacao Trigo-Sideracao-Trigo
Perda de Solo (t/ha)
3
2.5
2
1.5
1
0.5
0
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
Anos
Talhao 3
Talhao 4
Talhao 5
Talhao 6

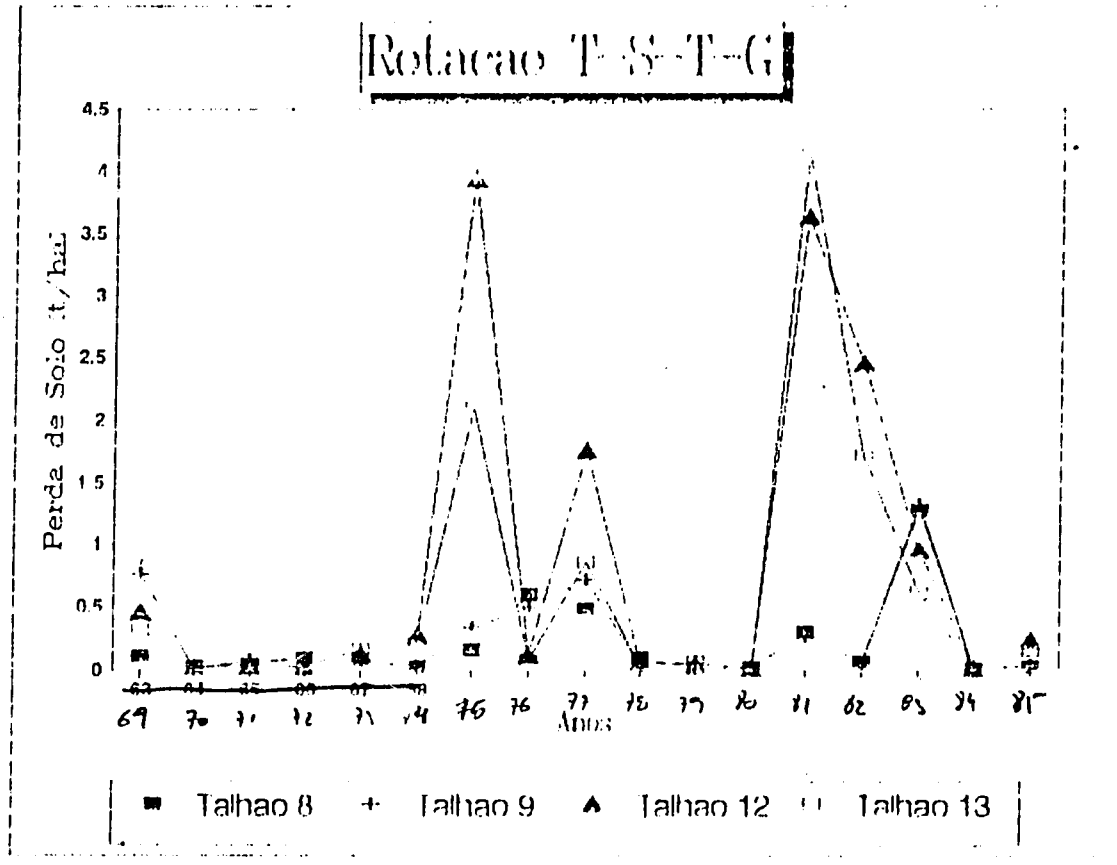

Rotacao T-S-T-G
Perda de Solo (t/ha)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
Anos
Talhao 8
Talhao 9
Talhao 12
Talhao 13

Fig. 7

Appendix 8

Table 1: Effect of exchangeable sodium percent (ESP) and water quality (deionized water-DW and tap water-TW) on dispersible clay of Hamra soil.

		DW suspension			TW suspension	
Soil ESP	Soil clay	Dispersed clay	EC	pH	Dispersed clay	EC
%	g kg^{-1}	%	dS m^{-1}		%	dS m^{-1}
2.2	180	27.1	.03	8.2	0	0.95
4.4	180	37.3	.030	8.24	0	0.95
16.0	140	93.4	.063	9.1	0	0.95

Table 2: Effect of soil ESP, slope and rain properties on final infiltration rate (IR) and cumulative soil losses (in 60 mm rain) from the Hamra soi

	5% slope		35% slope							
	DW rain		DW rain		TW rain		DW mist		TW mist	
Soil ESP	Final IR	Soil loss	Final IR	Soil loss	Final IR	Soil loss	Final IR	Soil loss	Final IR	Soil loss
%	$mm.h^{-1}$	$kg.m^{-2}$	$mm.h^{-1}$	$kg.m^{-2}$	$mm.h^{-1}$	$kg.m^{-2}$	$mm.h^{-1}$	$kg.m^{-2}$	$mm.h^{-1}$	$kg.m^{-2}$
2.2	2.2a	0.35a,b	5.2e	4.74h	7.3f	1.07d	3.7b,c	1.03c,d	3.5b	0.10a
8.0	1.6a	0.58a,b,c,d	5.1e	8.55f	8.3e	2.35e,f	5.0c,d,e	2.35e,f	4.0b,c,d,e	0.28a,b
19.0	1.6a	0.54a,b,c	3.8b.c.d	14.46j	4.3b,c,d,e	2.90f,g	5.0d,e	3.40g	7.5f	0.67b,c,d

* Figures followed by the same letter do not differ significantly at the 5% level (Tukey test)

Table 3: Effect of soil ESP, water quality and rain impact energy on the ratio between soil erosion at 35 and 5 percent slopes.

	Slope Ratio					
ESP	DW rain	TW rain	DW mist	TW mist	WEPP	USLE
2.2	13.5	3.1	2.9	0.3	2.3	17.4
8.0	14.7	4.1	0.5			
19.0	26.8	5.4	6.3	1.2		

Figure legend

Fig. 1: Sediment concentration in runoff as a function of cumulative rain for tap (a) and deionized (b) water (TW and DW respectively). Hamra soil at 35% slope and exchangeable sodium percentages (ESP) of 2.0, 8.0 and 19.0 respectively.

Fig. 2: Sediment concentration in runoff as a function of Cumulative mist for tap water (a) and deionized water (b) (TW and DW respectively). Hamra soil at 35% slope and exchangeable sodium percentages (ESP) of 2.0, 8.0 and 19.0 respectively.

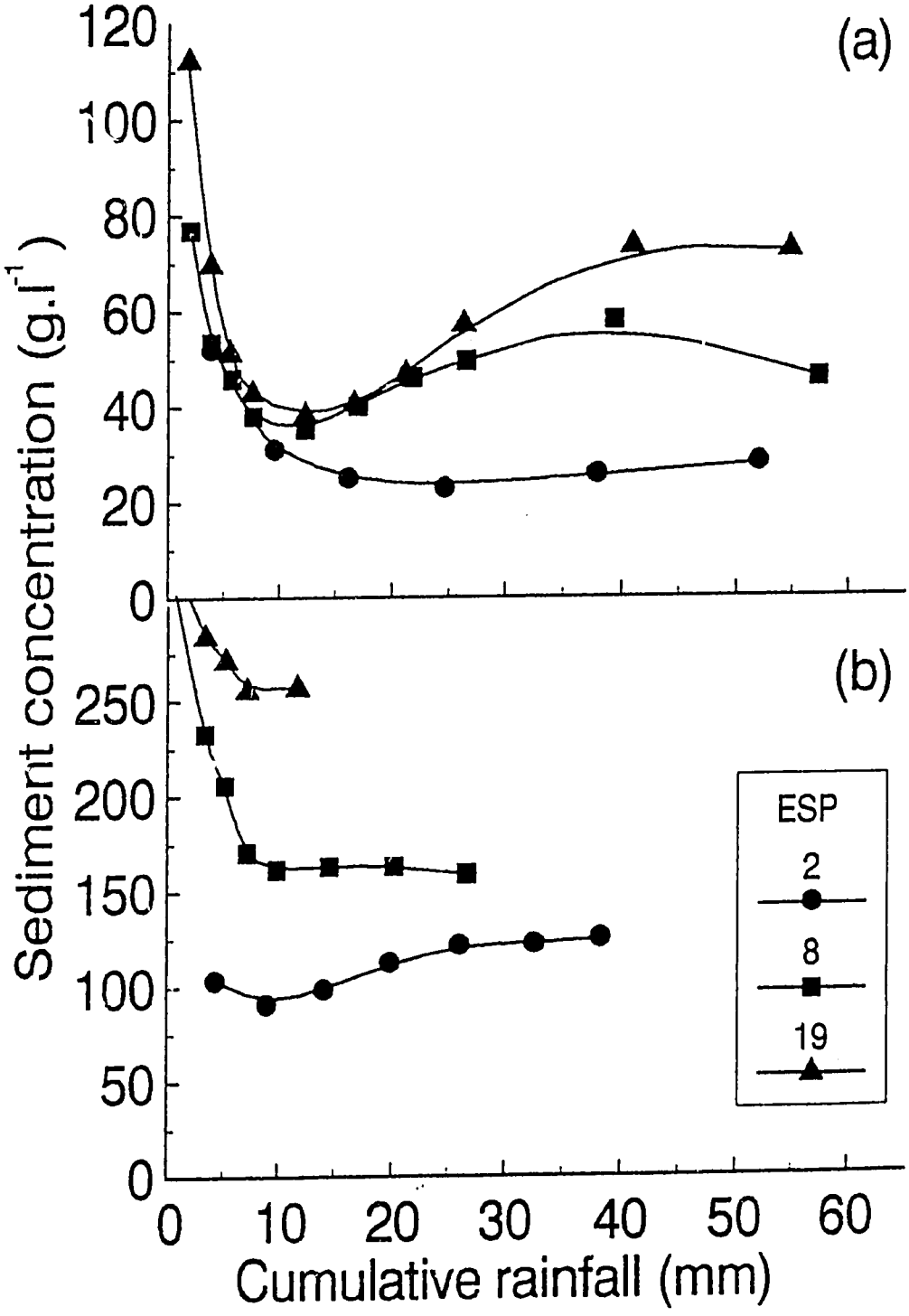

(a)
(b)
Sediment concentration (g.l-1)
Cumulative rainfall (mm)
ESP
2
8
19
0
20
40
60
80
100
120
0
50
100
150
200
250
0
10
20
30
40
50
60

Fig. 1

11

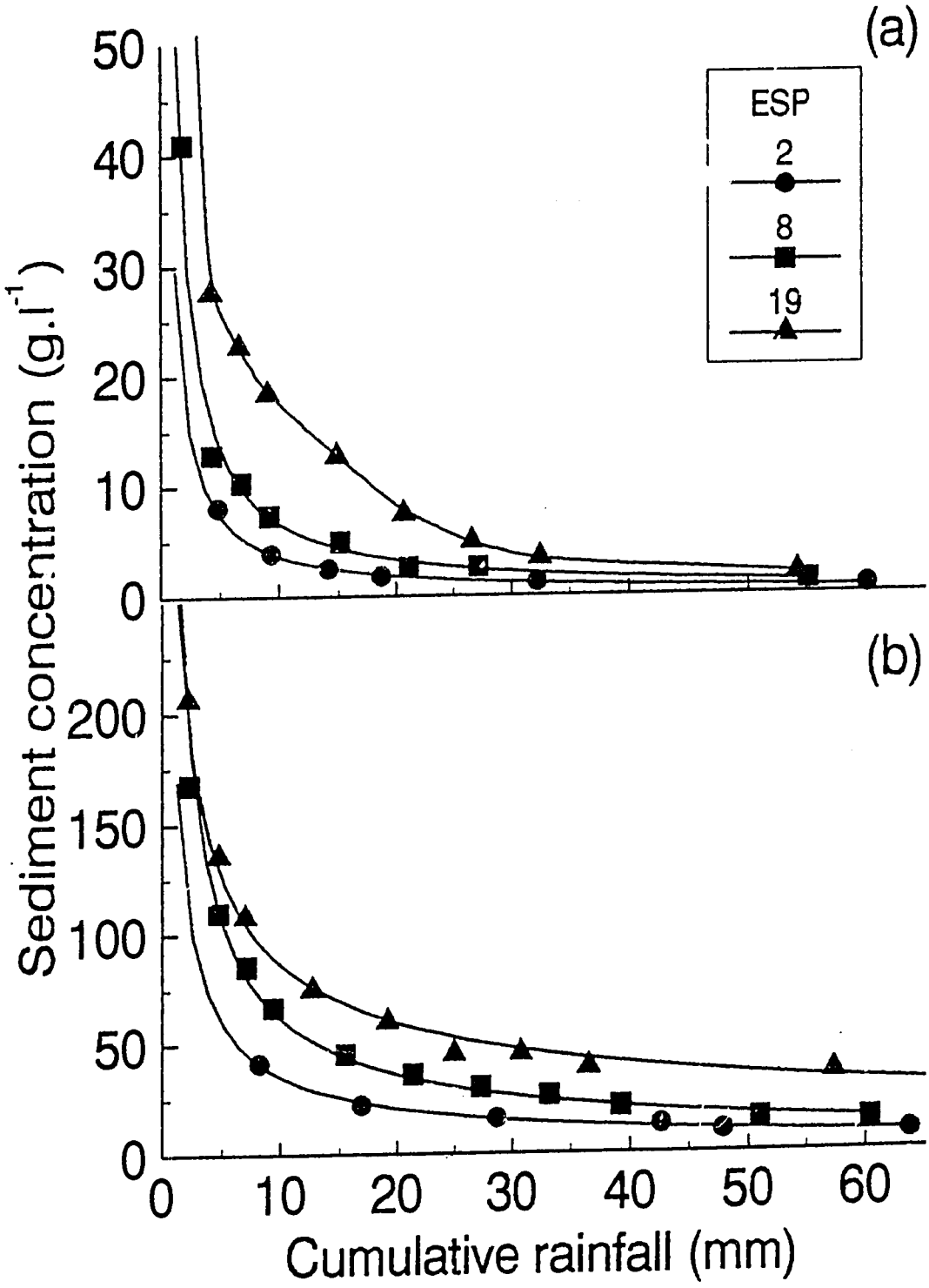

(a)
(b)
ESP
2
8
19
Sediment concentration (g.l-1)
Cumulative rainfall (mm)
0
10
20
30
40
50
60
100
150
200

Fig. 2

Appendix 7

Rainfall erosivity and the universal soil loss equation (USLE) suitability for Portugal.

1. Rainfall erosivity studies

For this study rainfall data from three stations, two in Lisbon (Sassoeiros and Portela) and one in Mertola (Vale Formoso) were used. For the Lisbon stations rainfall data from 1970/71 to 1983/84 were analyzed, and for the Vale Formoso station data from 1963/64 to 1985/86 were used..

1.1 Intensity-Duration-Frequency (IDF) curves

For the Lisbon stations, IDF curves were already developed. IDF curves for Vale Formoso have been developed using the following methodology:

a) For each storm the maximum rainfall amount in 15, 30, 60, 120, 180, 360, 720, 1080 and 1440 minutes was calculated.

b) For each duration the maximum rainfall intensity was obtained for each year.

c) The succession of maximum values for each duration has been adjusted to a Pearson III distribution law.

d) For each duration the rainfall intensity with recurrence interval of 2, 5, 10, 20, 50 and 100 years has been calculated and adjusted to the following type of curve using a linear regression:

90

$$I = aD^b$$

where:

I - maximum intensity (mm h^{-1})

D - storm duration (min)

a and b - constants

Correlation coefficients > 0.99 were observed for all cases.

Results for Lisbon and Vale Formoso for recurrence interval of 2 years are presented in Fig. 1. It can be noted that for durations greater than 60 minutes rain in Vale Formoso shows intensities smaller than that in Lisbon. For shorter durations the opposite was noted. This behavior was observed for all recurrence periods studied. The IDF curve indicates that there is a remarkable difference between rainfall erosivity at the coast and the inland of Portugal.

1.2 - Time distribution of rainfall in storms

For all storms cumulative rainfall vs. rainfall duration, both in a dimensionless form has been plotted. Each storm has been classified into one of 4 quarters, according to the quarter in which most of the rainfall occurred (Fig. 2). For the 262 storms studied we noted that the 4 types of storms had an equal occurrence. Hence, this type of rainfall classification was considered as non useful in rain erosivity studies.

81

2. The Universal Soil Loss Equation (USLE)

2.1. Vale Formoso Erosion Center

The Center is working since 1960 and is equipped with 16 erosion plots of 20.0 m long and 8.3 m wide. Slopes of the plots ranged between 10% and 20% and orientations from East to South-West. Various cultivation sequences were studied (Table 1).

2.2. Application of the USLE

The USLE model for prediction of soil loss is the following:

$$A = R\ K\ LS\ C\ P$$

where:

A - soil loss (ton ha^{-1} $year^{-1}$)

R - rainfall erosion index (ton ha^{-1} $year^{-1}$)

K - soil erodibility

LS - phisiographic factor

C - cover and management factor

P - support practice factor

For Vale Formoso R index of 97.1 ton ha^{-1} $year^{-1}$ and a K value of 0.44 were used. The C, P and LS factors (Table 1) have been obtained according to Whischmeier's methodology.

82

2.3. Results

A comparison between observed soil loss and that computed with the USLE is given in Table 2. The ratio between computed and observed soil loss ranges from 32 to 44 for all crop sequences excluding plots 1 and 2 where the ratio is 9.5.

2.3.1. Crop sequence: Bare soil (A) - Wheat (T)

Plots 1 and 10 and plots 2 and 11 have their crop sequence in phase. The slope of plots 10 and 11 is 16% and that of plots 1 and 2, is 10%. The soil loss from plots 10 and 11 was therefore expected to be greater but that was not the case. The observed soil loss from plots 1 and 2 was nearly twice that from plots 10 and 11 (Table 2).

Plots 1 and 2 should present identical soil loss but averages of 0.72 and 1.46 ton ha^{-1}, respectively were observed. Plots 10 and 11 showed a similar tendency with average values of 0.38 and 0.89 ton ha^{-1}, respectively.

Soil loss at the odd years was greater than that at the even years (Fig. 3). This observation can indicate a two year cycle for rainfall erosivity. This was amplified by less cover protection as higher soil losses were observed in plots 2 and 11 which had wheat in the odd years.

Plots 7 and 7x differ in their width being 8.3 and 4 m, respec-

93

tively. The two plots show similar soil losses for most years (Fig. 4). But in years where larger soil losses were observed, the narrower plot (7x) had much larger values than the second one. The soil loss averages were 0.17 and 0.42 ton ha^{-1}, respectively.

2.3.2. Crop sequence: Bare soil (A) - Wheat (T) - Barley (S) - Wheat (T) - Pasture (P) - Pasture (P)

Greater soil losses occurred at the wheat years (Fig. 5). Plots 9, 12 and 15 had wheat in the odd years and had an average soil loss of 0.4, 1.1 and 1.11 ton ha^{-1}, respectively. Plots 8, 13 and 14 had wheat at even years and gave an average soil loss of 0.10, 0.29 and 0.49 ton ha^{-1}, respectively. The differences can be related to different slopes and crops in each year.

2.3.3. Crop sequence: Wheat (T) - Barley (S) - Wheat (T)

Plots 3 and 4 and plots 5 and 6 had their crop sequence in phase. Soil losses for the 4 plots show a relative variation, 0.53, 0.61, 0.46 and 0.33 ton ha^{-1}, respectively (Fig. 6).

2.3.4. Crop sequence: Wheat (T) - Barley (S) - Wheat (T) - Barley(G,grains)

Greater soil losses occurred when wheat was grown. Plots 8 and 9 had wheat at the even years and plots 12 and 13 had wheat at the odd years. Consequently higher soil losses were observed

84

in the latter two plots (Fig. 7). The deleterious effect of wheat on soil erosion confirmed with the results from the other crop sequences.

2.4. Calibration of the Universal Soil Loss Equation (USLE)

From the results obtained the following can be concluded:

I. The USLE overpredicted soil loss by tenfold.

II. The ratio between computed and observed soil loss varied by a constant for each crop sequence.

III. Rainfall erosivity varied among years, especially between odd and even years.

Studying the various factors of the USLE led to the conclusion that the rain (R), soil erodibility (K) and cover and management (C) factors are the most sensitive ones. It was decided to concentrate on the R factor and thus to apply the USLE on a rainstorm basis rather than on an annual one.

Data collected in the Vale Formoso Erosion Center were used for this study. For each storm several erosivity indexes were calculated. A good agreement was found between EI30 and storm volume and storm duration. Comparisons of calculated results and soil loss data for different storms resulted in poor correlations. Consequently, the R factor was corrected using two coefficients as follows: aR^b. The "a" showed a large variation from storm to storm but the" B" remained fairly constant.

45

Slope, Aspect, and Phosphogypsum Effects on Runoff and Erosion

M. Agassi,* I. Shainberg, and J. Morin

ABSTRACT

The effect of slope, aspect (windward vs. leeward), and phosphogypsum (PG) application on rain amount, runoff, and erosion from a Grumusol soil (Typic Chromoxerert in Israel) was measured in small field plots (1 by 1.5 m) exposed to natural rainstorms. The amount of effective rain on the slopes, as measured with small rain gauges with orifices in a plane parallel to the slope, increased slightly on the windward aspect as slope increased to ~58% and decreased thereafter. On the leeward aspect, the amount of effective rain dropped steadily to half of the meteorological rain at a slope of 100%. The amount of runoff was not affected by slope on the windward aspect but decreased sharply on the leeward aspect as slope increased. PG releases electrolytes into the percolating and runoff water, prevents dispersion of the particles at the surface, stabilizes the soil structure, and reduced soil erosion. PG applied at 5 Mg ha^{-1} reduced runoff to about 25% of that in the control and reduced soil loss to 1 to 3% of that in the control. The dramatic effect of PG on erosion increased with slope steepness.

SOILS IN SEMIARID REGIONS are characterized by poor structure and relatively high sodicity in the soil profile. A major consequence of the lack or nonstability of aggregation is the tendency of these soils to display rapid surface sealing during rainfall, which induces excessive runoff and soil erosion.

Breakdown of the soil structure and formation of a seal at the soil surface are enhanced by the impact energy of the raindrops and the low concentration of electrolytes in rainwater (Agassi et al., 1981, 1985a). Agassi et al. (1981) proposed that seal formation is due to two complementary mechanisms: (i) physical disintegration of soil aggregates caused by the impact of water drops; and (ii) chemical dispersion, which depends on the exchangeable sodium percentage (ESP) and on the electrolyte concentration of the applied water. When water of high electrolyte concentration is used, chemical dispersion is largely prevented and a seal with high permeability is formed, mainly by the physical mechanism.

The beneficial effect of surface application of PG in maintaining high rain infiltration, reducing runoff, and preventing soil loss has been demonstrated in the laboratory (Agassi et al., 1982, 1985b; Kazman et al., 1983; Warrington et al., 1989). When PG is spread onto the soil, it dissolves and releases electrolytes that prevent clay dispersion. By preventing clay dispersion, surface-applied PG increased the permeability of the seal, tripled the final infiltration rate of a Typic Rhodoxeralf, reduced the amount of runoff by 50%, and reduced erosion to 10 to 40% of that in the control (Warrington et al., 1989).

The intensity at which a given rainfall is intercepted on the ground depends on the angle of incidence (Sharon, 1980; Sharon et al., 1988). Intensity is greatest for rainfall perpendicular to a surface, and decreases to zero for rain falling parallel to it. The angle of incidence depends on the position (i.e., both aspect and slope or gradient) of the ground, relative to the direction from which rain is falling. Thus, for a given direction of rain, the proportion of rain actually intercepted on the ground will vary with aspect or slope, or both. It is this quantity that is significant in rain-dependent processes taking place at soil surfaces.

Because soil slope and aspect influence the amount of rainfall intercepted, they should also influence the amounts of runoff and erosion. Our objectives were to (i) study the effect of slope and aspect (windward vs. leeward sides) on rain amount, runoff, and erosion from a grumusol soil in small field plots (1.5 m^2) exposed to natural rainstorms and, (ii) study the effect of PG, as spread onto different slopes and aspects, on runoff and erosion.

MATERIALS AND METHODS

Geography

The experimental sites were in the northern Negev of Israel near Kibbutz Bet Qama. The soil type was Grumusol (Typic Chromoxerert), with 48% clay, 25% silt, and 27% sand. The average cation-exchange capacity (CEC) was 37 cmol$_c$ kg^{-1} and ESP was 18. The $CaCO_3$ content was 13.4%.

Average annual rainfall at the site is 265 mm, with a CV of 38%. This is meteorological rainfall, without taking slope or aspect into account. ≥50% of the rain comes from a narrow section of ±20 to 25° around the azimuth of 240° (dominantly west-southwest winds) (Sharon et al., 1988). With these prevailing winds, rain falls mostly at a steep inclination. Resultant angles of 40 to 60° (from the vertical have been found in rainstorms with a wind speed of 10 m/s (Sharon, 1980). The effective rainfall actually incident on the windward (western) and leeward (eastern) sides of sloping ground deviates widely from measurements of meteorological rainfall made in conventional rain gauges with a horizontal orifice.

Runoff Plots and Instrumentation

Runoff plots (1.0 m by 1.5 m) were constructed at two sites, 2 km apart. The first site was on a natural wadi wall (Fig. 1a). The prevailing aspect of the slopes at this site was the southwest (essentially windward). The runoff plots were constructed on natural consolidated undisturbed slopes of 12, 31.5, and 65%. The soil at this site is variable, with ESP ranging between 10 and 20. For a second site, we chose a nearby roadcut (Fig. 1b). Slopes of 8.7, 57.7, and 100% were constructed at the roadcut site on the windward and leeward aspects and well-mixed undisturbed soil from the wadi wall was used to form the uppermost 5-cm layer on the roadcut slopes (Fig. 1b).

Two soil treatments were applied: bare untreated ground (control) and PG spread onto the soil surface at a rate equivalent to 5 Mg ha^{-1}. The soil surface at the undisturbed wadi site was cultivated just enough to break the previous crust, and then was smoothed by hand. Each treatment was replicated three times; thus, the number of plots at the roadcut site was 3 slopes × 2 treatments × 2 aspects × 3 replicates

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96

Fig. 1. Runoff plots on (a) natural wadi wall and (b) roadcut sites. In (b), only the 57.5% and 100% slopes are shown. (c) Effect of phosphogypsum (PG) on the soil surface at the steep (100%) windward slope. Note the soil collapse in the control compared with the PG treatment. (d) Effect of PG on the soil surface at the 8.7% slope, windward aspect (note the white PG aggregates).

= 36 plots, and at the wadi site it was 3 slopes × 2 treatments × 3 replicates = 18 plots.

Rain gauges were of the small-orifice (6.4 cm²) type. The gauges on the slopes were inclined, with the orifices on a plane parallel to the soil surface, to measure effective (rather than meteorological) rainfall. From each plot, runoff water together with its suspended solids collected in a triangular funnel (Fig. 1d), to flow gravimetrically through a pipe into a sunken container. After each rainstorm, the rain, runoff water, and suspended solids were measured. Samples of runoff water were dried in the oven and the concentration and amount of suspended solids were calculated.

RESULTS AND DISCUSSION

Measurements were conducted during the latter part of the 1987–1988 rainy season. We observed five rain storms at the disturbed-soil and roadcut site and six at the undisturbed-soil wadi site between January and March 1988. Rainfall totaled ~240 mm at both sites. A complete listing of rainfall, runoff, and soil losses for each storm is presented in Tables 1 and 2. The seasonal sum of rainfall, runoff, and erosion is presented in Fig. 2 to 4.

Table 1. Effective rain, runoff, and soil loss from 1.5 m² field plots on consolidated Grumusol soil at the wadi site (windward slopes), with and without phosphogypsum (PG) treatment.†

Date of rainstorm	Treatment	12% slope			31.5% slope			65% slope		
		Rain	Runoff	Soil loss	Rain	Runoff	Soil loss	Rain	Runoff	Soil loss
		mm		g m⁻²	mm		g m⁻²	mm		g m⁻²
5 Jan.	Control	28	14.1	42.6	28	13.5	97.8	27	8.4	297
	PG		3.3	5.4		3.0	6.8		3.1	8
17 Jan.	Control	47	25.2	78.2	45	22.3	346.0	40	26.2	2 640
	PG		6.9	9.7		7.5	36.2		4.5	47
3 Feb.	Control	41	20.2	50.0	42	22.7	235.4	43	27.3	597
	PG		6.7	7.4		9.5	50.0		4.6	14
18 Feb.	Control	58	30.8	110.3	58	35.5	375.6	49	34.8	3 607
	PG		7.7	5.1		10.8	28.5		5.3	58
24 Feb.	Control	52	23.8	44.9	54	30.8	32.3	44	30.0	988
	PG		6.1	2.9		11.8	47.2		9.3	56
7 Mar.	Control	23	11.2	19.6	23	7.9	58.6	20	10.5	2 928
	PG		1.9	0.9		1.0	2.8		1.4	5
Total	Control	249	125.3	345.6	250	132.7	1437.2	223	137.2	11 057
	PG		32.6	31.4		43.6	171.5		28.2	188

† Results are means of three replicates. The standard deviation values were always < 10% of the mean value.

27

Table 2. Effective rain, runoff, and soil loss from 1.5-m² field plots on disturbed Grumusol soil at the roadcut site (windward vs. leeward slopes), with and without phosphogypsum (PG) treatment.†

Date of rainstorm	Treatment	8.7% slope			57.5% slope			100% slope		
		Rain	Runoff	Soil loss	Rain	Runoff	Soil loss	Rain	Runoff	Soil loss
		mm		g m⁻²	mm		g m⁻²	mm		g m⁻²
					Western aspect (windward)					
5 Jan.	Control	27	15.8	110	28.5	11.0	200	23.7	3.9	40
	PG		2.5	0		2.1	0		2.0	0
17 Jan.	Control	73	44.2	410	82.0	35.0	1130	78.0	‡	‡
	PG		9.5	10		9.3	30		5.0	0
3 Feb.	Control	40	26.6	200	44.5	35.8	1600	41.2	‡	‡
	PG		10.1	10		9.8	20		6.7	80
18 Feb.	Control	56	46.7	310	60.0	44.5	2000	51.5	‡	‡
	PG		13.3	30		10.1	10		10.1	0
24 Feb.	Control	47	37.2	400	53.0	42.3	1000	51.3	‡	‡
	PG		12.2	20		14.5	0		12.2	10
Total	Control	243	170.0	1430	268.0	168.0	5930	245.7	–	–
	PG		47.6	90		45.8	70		36.0	90
					Eastern aspect (leeward)					
5 Jan.	Control	27	12.8	170	23.2	6.6	30	18.0	1.2	0
	PG		1.8	0		1.4	0		1.6	0
17 Feb.	Control	70	45.7	1000	50.0	14.7	160	27.0	4.5	10
	PG		12.4	50		[illegible]	10		2.2	0
3 Feb.	Control	41	29.9	380	33.5	17.1	160	20.7	3.6	170
	PG		7.9	10		5.9	10		2.9	0
18 Feb.	Control	57	44.0	350	51.7	24.3	370	39.0	9.6	10
	PG		9.4	10		6.5	10		5.1	0
24 Feb.	Control	46	38.6	410	33.8	21.2	210	20.8	7.4	20
	PG		9.4	0		3.9	0		3.9	0
Total	Control	241	171.0	2310	192.2	83.9	930	125.0	26.3	210
	PG		40.9	80		23.2	30		15.7	10

† Results are means of three replicates. The standard deviation values were always <10% of the mean value.
‡ Landslide.

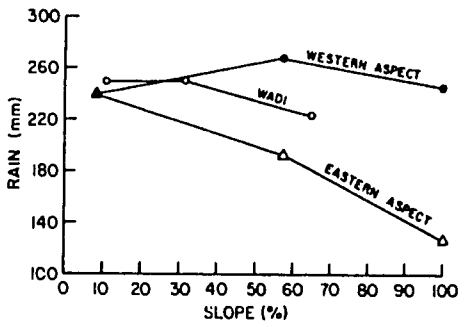

Fig. 2. Effective rainfall during the rainy season as affected by soil slope, aspect (western or windward vs. eastern or leeward), and location (wadi or consolidated soil vs. roadcut or disturbed soil). The wadi site was windward aspect only; the other two lines show roadcut data.

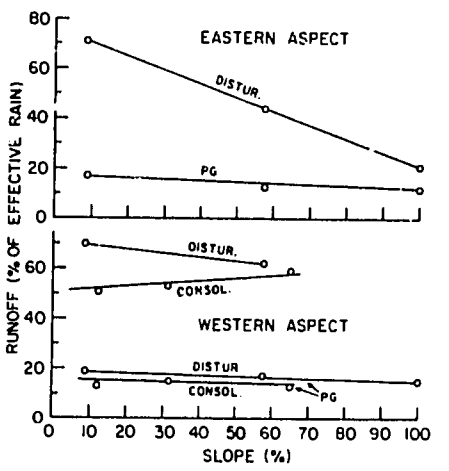

Fig. 3. Percent of runoff from effective rainfall during the rainy season as affected by soil slope, aspect (western or windward vs. eastern or leeward), location, and surface treatments (with or without phosphogypsum [PG]).

Rainfall Measurements

The total depth of rain measured with standard rain gauges with horizontal orifices at the wadi and roadcut sites was 240 and 249 mm, respectively. The amount of effective rain on the slopes is presented in Tables 1 and 2 (for each of the single storms) and in Fig. 2 (for the total season rainfall). It is evident that the effective rain is a function of both slope and aspect. As noted above, the dominant wind direction during rainstorms is from the west-southwest, and so the amount of incident rain is higher on the western than on the eastern aspect. The maximum amount of incident rain on the western aspect was at the intermediate slope (57.5%). It can be inferred that at this slope on the windward (western) aspect the incident rain was perpendicular to the soil surface, because at greater or lesser slopes, the effective rain decreased. On the leeward slope (eastern aspect), the amount of effective rain decreased continuously with increase in slope. At slopes of 57.5 and 100%, the effective rain dropped to 0.77 and 0.50 of the meteorological rain.

Runoff Measurements

The amounts of runoff (mm) as a function of slope and treatment for each storm at the two sites and the

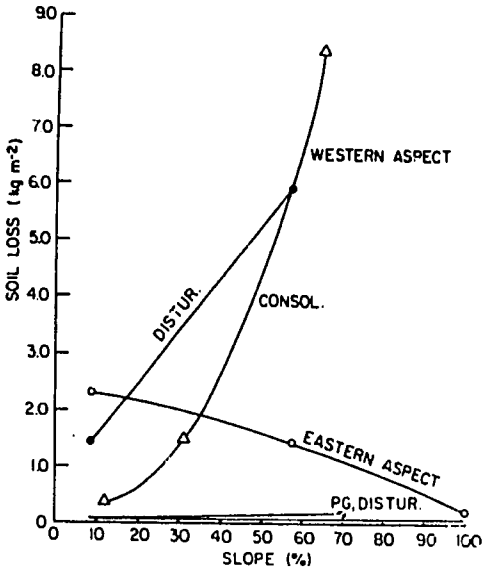

Fig. 4. Soil loss during the rainy season as affected by soil slope, aspect (western or windward vs. eastern or leeward), location (disturbed soil at the roadcut site vs. consolidated soil at the wadi site), and surface treatments (with or without phosphogypsum [PG]). For PG on disturbed soil, the upper line shows the windward aspect, and the lower line, leeward.

two aspects are presented in Tables 1 and 2. The fraction of runoff (from effective rain) as a function of slope is presented in Fig. 3. The following characteristics should be noted.

1. On the windward aspects, the net effect of slope on runoff was small because of an interplay between surface sealing and surface erosion. The percent of runoff increased with an increase in slope on the consolidated surfaces, whereas it decreased with an increase in slope on the disturbed surfaces. Averaging across both surfaces, the percent of runoff in the control treatment was ~60% of the effective rain. The high runoff (and low infiltration) was due to seal formation at the soil surface (Agassi et al., 1981). Similarly, the impact of raindrops, combined with the low concentration of electrolytes in the water and the inherent low stability of the soil structure, caused the infiltration rate of another Grumusol to drop to equilibrium values of 2 to 3 mm h^{-1} after 75 mm of simulated rainfall (Agassi et al., 1985a). With an increase in slope, runoff increases because surface storage decreases. However, soil erosion also increases with an increase in slope, and the seal at the soil surface is eroded. A high rate of seal erosion leads to increased infiltration and decreased runoff (Warrington et al., 1989). The net effect of the two opposing processes was that runoff was affected only slightly by slope. This was true for the treated as well as the control surface.
2. The effect of PG treatment on runoff percentage was pronounced (Fig. 3). The percent of runoff in the PG treatments was about 15%, which was one-fourth of that in the control. It has been shown (Agassi et al., 1982, 1985a, 1985b; Gal et al., 1984) that PG reduces surface sealing by raising the electrolyte concentration in the solution at the soil surface, thus reducing the dispersion of soil clays and preventing the formation of a *washed-in* layer. Since the seal forms more slowly and is more permeable on soil surfaces treated with PG, runoff is reduced.
3. Differences in runoff between the consolidated, undisturbed slopes and those from the disturbed slopes were small (Fig. 3). Since seal formation determines the rate of infiltration and since seals formed at the surfaces of both disturbed and consolidated soils, the properties of the soil underneath the seal affected only slightly the rate of infiltration.
4. The amount of effective rain on the leeward side of the dominant wind (eastern aspect) decreased with slope (Fig. 2). At this aspect, the percent of runoff from effective rain decreased sharply with increasing slope, from 70% at 8.5% slope to about 20% at 100% slope (Fig. 3). The low values of runoff from the steep slopes suggest that the seal was not fully developed on the leeward aspect. In a study of the effect of impact energy of raindrops on seal properties of a loess soil, Agassi et al. (1985a) found that the impact energy of raindrops is essential for seal formation and when rain without energy was applied, high infiltration rates were maintained. In the leeward side of the dominant wind, both the amount of rain and the impact energy of raindrops were low; thus, a seal with high permeability was formed, and the percent of runoff was low.
5. On the leeward aspect, the relative efficiency of PG in preventing runoff was high at the gentle slope but diminished as the slope increased. The beneficial effect of PG was most pronounced in dispersed soils exposed to the beating action of raindrops. As the impact of raindrops decreased, the formation of the seal decreased and the beneficial effect of PG was less pronounced.
6. Finally, it should be noted that no runoff data are available for the control treatment of the 100% slope on the windward aspect. Total collapse of the surface layer with localized landslides took place in the three replicates of this treatment (Fig. 1c). Conversely, no landslides occurred in the PG treatments in spite of the fact that more rain infiltrated this treatment than the nontreated plots. It seems that the low concentration of electrolytes in the rain and the dispersivity of the soil (high ESP) led to soil slide. When PG was spread on the soil, the relatively high concentration of electrolytes in the soil solution prevented clay dispersion and soil slide in spite of the greater rain water percolation.

Soil Erosion

The effect of slope on soil loss for the two sites is shown in Tables 1 and 2. The effect of slope on the season soil losses is presented in Fig. 4. The following should be noted:

1. On the windward aspect (Table 2), increases in slope had a dramatic effect on soil losses. The

effect of the topographic factor (length × slope) was quite similar to that calculated by Wischmeier and Smith (1978). There was no significant difference in soil loss between the disturbed and consolidated plots.

2. Treatment with PG reduced soil loss dramatically (Fig. 4). The effect of PG in reducing erosion increased with slope steepness. At the gentle slope, PG treatment reduced soil losses to 6 to 10% of that in the control, whereas at the intermediate slope, PG treatments reduced erosion to 1 to 3% of that in the control. At 100% slope, the landslide that occurred in the control prevented a comparison with the PG treatment. The effect of PG on erosion should be compared with that on runoff. Treatment with PG reduced runoff from ~60% in the control to ~15% in the treated soil, influenced only slightly by slope (Fig. 3). These observations suggest that the beneficial effect of PG in decreasing erosion is due not only to decreased runoff but also to decreased sediment concentration. Similar observations were obtained in laboratory studies using rain simulators (Warrington et al., 1989).
3. The effect of PG on the shape of the soil surface at the steep (100%) and gentle (8-7%) slope is shown in Fig. 1c, and 1d, respectively. After 140 mm rain, the surface of the untreated soil at the gentle slope was smooth and the aggregates were completely destroyed. Naked white sand grains from which the clay particles had been removed by clay dispersion give the white color to the surface (Fig. 1d). Soil treated with PG maintained part of its original structure, the surface was not as smooth, and no naked sand grains were observed on the surface. The well-developed seal at the soil surface of the control caused the high runoff and erosion. Increasing the slope angle increased the velocity of the water flowing over the soil surface, and intensive rill and interrill erosion took place. The PG-treated soils did not develop intensive erosion or rills even at the 100% slope (Fig. 1c). It is hypothesized that the presence of electrolytes in the runoff of the PG treated soils decreased rill formation and rill erosion. This process, which supplements the decrease in runoff, may account for the dramatic effect of PG in reducing erosion.
4. On the leeward aspect, soil losses decreased with increase in slope, because of the decrease in rain intensity (Fig. 2), which was followed by a decrease in the percent of runoff (Fig. 3). As the slope increased from 8.7 to 100%, the amount of effective rain dropped to 125 mm (52% of the meteorological rain), the runoff dropped to 26.3 mm (15% of the amount of runoff at 8.7% slope), and the soil losses dropped to 210 g (9% of the soil loss at 8.7% slope). A similar relationship was obtained at the intermediate (57.7%) slope. The similarity, on the leeward aspect, in the effect of slope on runoff and soil loss suggests that these two processes are related. We can assume that the impact energy of raindrops on the soil surface in the leeward side of the wind diminished even more than the rain intensity. With the decrease in impact energy, both seal formation and soil detachment were also diminished.

SUMMARY AND CONCLUSIONS

The amount of effective rain on the slopes, as measured with small rain gauges with orifices in a plane parallel to the slope, increased slightly on the western (windward) aspect as slope increased to ~58% and decreased thereafter. On the leeward aspect, the amount of effective rain dropped steadily with slope, to half of the meteorological rain at a slope of 100%. The amount of runoff was not affected by slope on the windward aspect but decreased sharply on the leeward aspect as slope increased.

These findings are relevant to design and engineering for runoff and erosion control on steep slopes, as well as site selection for field experiments.

The effect of PG on soil loss reduction operates by several mechanisms (Warrington et al., 1989). First, PG spread at the soil surface dissolves and releases electrolytes into the percolating and runoff waters. The high concentration of electrolytes in the percolating water slows or prevents the formation of the seal and increases the fraction of rain that penetrates into the soil, thus decreasing the depth of runoff water. Second, increasing the electrolyte concentration at the soil surface also prevents the breakdown and dispersion of the aggregates at the soil surface. Stable aggregates are less transportable by raindrop detachment and overland flow. Third, rill formation and rill erosion are slowed by the presence of electrolytes. Finally, in the presence of electrolytes in the runoff water, deposition of clay particles from runoff water is enhanced (Rose, 1985). The dramatic effect of PG in reducing runoff and erosion from steep slopes shows the influence of water quality and soil properties on erosion. Our results may be applied in stabilizing soil structures with steep slopes. Further research should include other unstable soils from semiarid regions.

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90

Appendix 6

Soil Dispersibility Rain Properties and Slope Interaction in Rill Formation and Erosion

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Abstract

Soil erosion increases with slope steepness. We hypothesized that the rate at which soil erosion from short slopes increases with slope depends on the prevailing erosion mechanism which depend on soil dispersibility and rain properties (impact energy of drops and water quality). Soil dispersion as a function of exchangeable sodium percentage (ESP) and water quality was determined by shaking soil samples with distilled water (DW) or tap water (TW). Clay dispersion increased with increase in soil ESP and was prevented by the electrolyte concentration in TW. The effect of soil ESP, water quality and the impact energy of rain on soil erosion while maintaining similar runoff was studied by exposing first the soil samples to DW rain on 5% slope until seal was developed. Then the slope was increased to 35% and the water quality and impact energy of the rain were changed. Runoff volumes were unaffected by rain properties at the 35% slope. Soil losses increased with increase in the ESP of the soil and varied with rain properties in the following order: DW rain > TW rain = DW rain with low energy (mist) > TW mist. In the DW rains (both high impact energy and mist) rills were formed. Extent of rilling increased with soil ESP. No rills were formed in TW rains. Under dispersive conditions (sodic soils and DW) runoff was sufficient to initiate rilling and soil losses increased sharply with slope.

Soil erosion by water involves (1) detachment of soil material from the soil mass by raindrop impact and/or runoff shear and 2) transport of the resulting sediment by raindrop splash and/or flowing runoff. The susceptibility of the soil to erosion is termed its erodibility. Soil erodibility is one of the key factors, along with rainstorm characteristics, topography, cover and management that determines the erosion resulting from rainstorms. It is commonly quantified as the K-factor in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). Several researchers, (Römkens et al. 1977; Wischmeier and Mannering, 1969) have developed equations for predicting soil erodibility values from soil properties such as texture, adhesiveness and aggregation. The USLE K-factor is an average annual value that combines two different types of erosion processes, rill erosion and interrill erosion.

The USLE equation also expresses the change in soil loss, A, per unit area, as a function of slope steepness, in degrees

$$A = 65.41 \sin^2\theta + 4.56 \sin\theta + 0.065 \qquad (1)$$

(Wischmeier and Smith, 1978). Using these relationships, soil loss per unit of area would increase nearly 15 times as steepness increases from 5% to 30%.

However, several studies of the effect of slope steepness on erosion from short slopes have shown that soil loss from such interrill areas is affected much less by steepness than the losses as expressed in the USLE (Singer and Blackard, 1982;

Watson and Laflen, 1986). A slope steepness factor for interrill areas

$$Sf = 1.05-0.85 \exp(-4 \sin \theta) \quad (2)$$

has been recommended for use in the Water Erosion Prediction Project (WEPP) and is supported by the data collected in the field research program (Liebenow et al. 1990). This relationship indicates that the erosion from short slopes doubles as the steepness increases from 5% to 30%.

Meyer and Harmon (1989) studying the effect of slope length and steepness on erosion for several soils concluded that slope length and steepness affected erosion most for the more erodible soils where rilling occurred. Warrington et al. (1989) observed that erosion from an unstable and dispersive soil depended on water quality. Change in slope angle from 5 to 25% doubled soil loss in a gypsum treatment which added electrolytes to the rain water, but increased by seven fold soil loss for the control treatment exposed to distilled water rain. On the 0.5 m slopes rilling occurred only in the control treatment (Warrington et al. 1989). Thus, we hypothesized that soil erodibility, rilling, and the effect of slope on erosion are related to soil dispersibility criteria. When dispersive conditions prevail (dispersive soils with low salt concentration rain) soil losses increase sharply with slope steepness. Conversely, when non dispersive soil is rained upon, or when dispersive soil is rained upon with electrolyte solution, soil loss increases only moderately with slope.

While soil dispersion has been implicated in reduced permeability and crusting of soils (Agassi et al. 1981, Kazman et al. 1983, Shainberg and Letey, 1984), its effect on soil erosion is less documented. Middleton (1930) suggested that the water-dispersibility of clay might relate to soil erosion, and Miller and Baharrudin (1986) found that a number of southeastern U.S. soils were dispersible by shaking in water, and that a good correlation exists between dispersibility and soil erosion. Similarly Singer et al. (1982) found that soil erodibility increased significantly with the addition of as little as 2% Na to the exchange complex..

Soil dispersion depends on the mineralogy of the clay, the chemical composition of the exchangeable cations and the electrolyte concentration of the soil solution (Oster et al. 1980). Clay dispersion increases with an increase in soil ESP and a decrease in solution electrolyte concentration (Shainberg and Letey, 1984). Emerson (1967) classified aggregates by their slaking and dispersion behavior, noting that some aggregates spontaneously dispersed in water while others dispersed only with mechanical disturbance. Spontaneous dispersion was later found to occur in soils with sodium adsorption ration (SAR)>3, given a sufficiently low solution ionic strength, whereas many soils with SAR<3 were dispersible only with mechanical energy input (Rengasamy et al. 1984). Soil surfaces exposed to high energy rain are mechanically dispersed and are more dispersible that

clay at surfaces exposed to low energy rain. The objectives of this study were to measure the effect of ESP, the EC of rain water (DW and TW), and the impact energy of rain drop (high energy rain and low energy rain = mist) on soil erosion processes and the slope factor.

ESP of the soil, electrolyte concentration in the rain and raindrop impact energy affect infiltration rate (IR) and runoff from soils (Agassi et al. 1981, 1988, and Kazman et al. 1983). Our objective in this study was to evaluate the effect of these parameters on erosion while maintaining IR and runoff as unaffected as possible by these parameters. Thus we had to develop a less conventional methodology. This methodology is based on the observation (Agassi et al. 1988) that once a seal is fully developed (by applying high energy DW rain until a steady IR is maintained) the hydraulic properties of the seal are not affected by switching to a rain with no impact energy (mist) or to saline water rain. In this study, the soil samples were first exposed to 60 mm DW rain on 5% slope (steady state IR values were obtained in < 50 mm). Infiltration, runoff and soil loss at the 5% slope were recorded. Then the slope was increased to 35% and the properties of the rain (energy of drops and electrolyte concentration of the water) were changed and infiltration runoff and erosion recorded.

Materials and Methods

A sandy loam soil material (Hamra, Typic Rhodoxeralf) from the coastal plain of Israel (Morasha) was used in this study. The clay, silt, and sand fractions of the soil material were 18, 7, and 75%, respectively. The dominant clay mineral was smectite with some kaolinite. The cation exchange capacity (CEC) was 11.7 $cmol_c kg^{-1}$ and the organic matter content was 5g kg^{-1}. Naturally occurring soil samples with ESP values of 2.2, 8.0 and 19.0 were used for the erosion studies and ESP values of 2.0, 4.4 and 16.0 were used in the dispersion tests. The difference in ESP values between the samples of the two experiments is due to differences in sampling time and location.

Soil Erosion Methodology

Soil samples were air dried, crushed to pass a 4-mm sieve, and thoroughly mixed. Layers of the soil material, .02 m deep, were packed into 0.3 m by 0.5 m perforated metal boxes, over an .08 m layer of coarse sand. The sand allowed free drainage of water to an outlet pipe set in the base of the box. The boxes were placed under a rainfall simulator (Morin et al. 1967) on a supporting framework. The slope angle of the box could be adjusted between 0 to 35%.

The samples were first saturated slowly (~ 2h.) with TW from the base. The composition of TW was Na-3.6 mol m^{-3}, Ca- 3.1 mol m^{-3}, Cl- 8.7 mol m^{-3}, EC - 0.95 dS m^{-1}, pH - 7.3) The samples were then subjected to a rainstorm with DW having an intensity of

35mm h^{-1} for 90 min. Rainstorm parameters were: median raindrop diameter, 2.3 mm; median drop velocity, 6.74 m s^{-1}; and total kinetic energy, 801 J $h^{-1}m^{-2}$. Runoff samples were collected at regular intervals. The volume of runoff and the mass of the soil it carried were measured. The volume of the effluent was collected and measured at 2-min intervals and the IR was calculated. When steady state IR was obtained (< 50 mm rain) the slope of the box was increased to 35%, the rainstorm characteristics were changed and infiltration, runoff and erosion recorded. The following rain properties were studied with the sample box at the 35% slope angle: (a) high energy with intensity of 35 mm h^{-1} DW rain (b) high energy with intensity of 35 mm h^{-1} TW rain (c) DW mist at 35 mm h^{-1} (d) TW mist at 35 mm h^{-1}. Both runoff and soil losses were determined. Four replicates were carried out for each treatment.

Clay Dispersion Measurements

The effect of exchangeable sodium and water quality on clay dispersion was studied by using soil samples with different exchangeable sodium levels (2.2, 4.4 and 16%), and by using TW and DW. Soil samples (13 g) were weighed into 50 ml centrifuge tubes to which 30ml of DW was added. The tubes were shaken moderately by hand for thirty seconds, centrifuged, and the EC of the supernatant was measured. If the EC of the supernatant exceeded 0.10 dS m^{-1}, the washing procedure was repeated until EC<0.1 dSm^{-1}. This washing procedure removed excess salts from saline samples. The soil samples were then transferred to 250 ml

plastic bottles. DW was added to the clay bottles to a volume of 200ml. to obtain a soil: water weight ratio of 1:15. The soil samples were shaken in a horizontal shaker for 15 minutes at a speed of 125 rpm. Thereafter, the bottles were left to stand for 4h. Twenty ml of suspensions were then siphoned from a depth of 50 mm, oven dried and the amount of clay determined gravimetrically. The EC and pH of the suspensions were also determined. Three replicates were carried out for every soil sample. In the TW treatments, TW was used instead of DW in the dispersion test.

Results and Discussion

Clay Dispersibility

The amount of clay dispersed (presented as percent of the total amount of clay in the soil) as a function of ESP of the Hamra soil and the water quality (DW and TW) is presented in Table 1. As expected, soil dispersibility increased with an increase in the ESP of the soil. A small increase in the amount of exchangeable Na had a considerable effect on the dispersion of the clay (Table 1). Similar effects of exchangeable Na on the flocculation value and electrophoretic mobility of Na/Ca montmorillonite have been reported (see Shainberg and Letey, 1984). The large effect of small percentages of Na was explained by a demixing model which postulates that Na concentrates on the external surfaces of the clay tactoids and Ca concentrates on the internal surfaces (Shainberg and Letey, 1984). The preferential

100

adsorption of Na on the external surfaces accounts for the high activity of Na in dispersing the clay tactoids. The data in Table 1 also demonstrates that the electrolyte concentration in the tap water (EC=0.95 dSm^{-1}) exceeded the flocculation value of the clay and prevented its dispersion. Therefore, when TW is rained on the Hamra soil with ESP$\leq$16 the electrolyte concentration exceeds the flocculation concentration and prevents clay dispersion. Thus, by comparing soil erosion with DW and TW, the contribution of clay dispersion to soil erodibility may be evaluated.

Infiltration Rate

The effect of soil ESP and rain electrolyte concentration on the IR curves of various Hamra soils at 5% slope have been reported by Agassi et al. (1981), Kazman et al. (1983), and Warrington et al. (1989). Whereas the initial hydraulic conductivity of this soil is very high (~100 mm h^{-1}), the IR dropped sharply when exposed to DW rain (< 50 mm) to final IR values of 2.2, 1.6, and 1.6 mm h^{-1} for the soil samples with ESP 2.2, 8.0, and 19.0 respectively (Table 2). The rapid drop in the IR demonstrates that the Hamra soil, even with an ESP of 2.2, is very susceptible to surface sealing. The increase in ESP from 2.2 to 8.0 resulted in a more rapid drop in IR and a decline in final IR (from 2.2 to 1.6 mm h^{-1}). A further increase in the ESP did not change the final IR values. Similar results were obtained by Kazman et al (1983) who postulated that the soil surface was susceptible to very low ESP values because of the

beating action of raindrops, which enhanced clay dispersion (Rengassamy et al., 1984).

When the steady state IR at 5% slope was reached, the slope was increased to 35% and the soil trays were subjected to rains of two energy rates and two water quality levels. The final IR values at the 35% slope as a function of the treatments are presented in Table 2. The final IR of the DW rain increased significantly with increase in slope steepness. This increase in the final IR with slope is associated with increase in soil erosion (Table 2) and was related to seal erosion (Poesen, 1986; Warrington et al. 1989). However, the differences in the final IR at 35% slope among the various ESP treatments is small ($\leq$ 1.4 mm h^{-1}) and the volume of runoff was considered to be unaffected by the ESP treatments. Raining with TW on the Hamra soil at 35% slope increased the final IR values (Table 2). These final IR values were not significantly higher than the corresponding values for the DW rain treatments with the exception of the soil with ESP 2.2 (Table 2). Erosion of the original seal and formation of a more permeable seal under less dispersive condition explain these results (Agassi et al., 1981, 1988). DW mist also increased the final IR of the soil samples at the three ESP values. The drop impact mechanism does not operate with mist thus producing less soil erosion than rain with DW. However there is sufficient film flow to cause seal erosion thereby increasing the final IR at the 35% slope (Table 2) as compared to the 5% slope condition. Soil erosion was also the mechanism

102

causing the final IR of the TW mist at 35% slope to increase (Table 2).

The final IR data presented in Table 2 demonstrated that once the seal was fully developed (at the end of the DW rain in 5% slope) switching to a DW rain with low energy or to TW rain with high or low impact energy had only a small effect on the final IR, and consequently only a negligible effect on runoff. Thus this methodology enables us to study the effect of rain properties and slope on soil erosion while maintaining runoff constant.

Soil Erosion

Concentration of sediment in the runoff from the soil trays at 35% slope are presented in Figs. 1 and 2. Since runoff rate as a function of rain depth (and time) is constant, Figs. 1 and 2 also present erosion rate ($g\ m^{-2}\ mm^{-1}$ or $g\ m^{-2}\ min^{-1}$) as a function of rain depth (or time). The erosion rate relationships may suggest the mechanisms which operate and control soil detachment. Thus, considering Figs. 1 and 2 the following observations, can be made:

When DW mist was applied (Fig. 2) the sediment concentration dropped exponentially from a very high value($150-250 g.l^{-1}$) to values $<50\ g.l^{-1}$. The increase in the slope from 5 to 35% and the resulting increase in flow velocity and transport capacity of runoff increased transport of the already dispersed and detached

(by raindrops) soil particles which were present at the soil surface. Thus the initial sediment concentration and erosion rate was very high. As the amount of detached particles was depleted, the erosion rate rapidly decreased. Soil ESP had a significant effect on the sediment concentration and erosion rate (Fig. 2) and on the cumulative soil loss (Table 2). An increase in ESP from 2.2 to 8.0 and 19.0 doubled and tripled the cumulative soil losses, respectively. Also shallow and deep rills developed at the moderate and high ESP levels, respectively. Evidently, the flow velocity and flow shear that was maintained at 35% slope and about 30 mm of runoff in combination with the low electrolyte concentration in runoff and the high dispersibility of the moderate and high ESP soils, caused the initiation and development of rills at the soil surface. The intensity of rilling increased with an increase in the soil ESP. The differences in erosion rates between the ESP treatments (Fig. 2) reflect the degree of rilling. Rain drop impact is therefore not essential for rill initiation and formation. However as will be discussed below, rain drop detachment and sediment transport to the rills contribute to high soil erosion rates.

When TW mist was applied, the initial erosion rates were about one fourth of the erosion rate with DW mist (Fig. 2). Also the sediment concentration and erosion rate dropped to < 3 g l^{-1} compared with erosion rates in the range of 15-50 g l^{-1} with DW mist (Fig. 2). No rills were observed in the TW mist.

Flocculation and deposition of the already detached soil particles account for the low initial concentration of sediment in runoff (Fig. 2). Since no rills were formed in the TW mist treatment, and since there was no significant soil detachment by mist impact, the erosion rates dropped asympotically to zero (Fig. 2). The effect of ESP in the presence of TW was significant only between the extreme ESP values (Table 2). Since the concentration of electrolytes in TW exceeds the flocculation value of the clay, soil dispersion was prevented as was rill development. These results suggest that rill formation in sodic soils depend on flow velocity and water quality. When dispersive conditions dominate (DW) the critical shear for rill initiation and rill erosion is low, rills are formed and soil erosion is significant. When soil dispersion is reduced by the electrolyte concentration in rain water, rills are not formed and soil losses are small.

When DW rain was applied, the erosion rate was initially very high and was maintained at high values throughout the rain (Fig. 1b). Deep rills (0.5-0.75 cm deep and 2 cm wide) were observed even in the low ESP soil similar to those reported in picture 4 by Warrington et al. (1989). Depth and extent of the rills increased with increase in the soil ESP. The combination of drop detachment, high flow velocity, turbulence introduced by drop impact, and highly dispersive conditions caused high erosion rates. As the soil ESP increased the soil erosion rate (Fig. 1) and cumulative soil loss (Table 2) also increased. The erosion

rate at ESP 19 was 2-3 times the erosion rate at ESP 2.2. The erosion was so severe in the high ESP soil that raining had to be discontinued much earlier than planned (Fig. 1).

When TW rain was applied, the erosion rates dropped sharply (Fig. 1) and the effect of ESP was less evident. The initial erosion rate with TW rain was higher than the corresponding value with TW mist due to soil detachment and the turbulence induced by impacting rain drops. However, the initial erosion rate in TW rain was below that in DW mist. This can be explained by two mechanisms: a) the high deposition rate with TW rain diminishes the sediment concentration when compared with DW mist, and b) erosion with DW mist is caused by rill flow whereas TW rain erosion is caused by uniform flow. The difference in transport capacity of rill and uniform interrill flow may explain the difference in the initial erosion rates. Erosion rate initially decreased to a minimum (at rain depth of 10-20 mm) and increased moderately thereafter. The shear strength of the seal that was formed under DW rain at 5% slope was high and controlled erosion. As this seal was eroded, a new seal was formed under TW rain. The new seal was less dispersive, more permeable and weaker in shear strength. Thus the erosion rate increased. Rills were not formed in the TW rain and the soil losses were due to rain detachment and transport capacity of the runoff flow.

The cumulative soil loss as a function of cumulative rain for the various treatments is presented in Table 2. It is

evident that the amount of soil loss (kg m^{-2}) per 60 mm storm is a function of water quality, drop impact energy and soil ESP. Soil losses increased with an increase in the soil ESP and with drop impact energy, and decreased with an increase in the electrolyte concentration in the rain. Considering the data in Table 2, it is noted that i) The effect of soil ESP is more pronounced when DW is applied. Use of TW tends to mask the differences caused by soil ESP. ii) In spite of the fact that in the DW mist treatment rills were formed, the amount of soil loss was low and was comparable to the amount of soil loss in TW rain. In the absence of raindrop impact, soil detachment and interrill erosion is prevented and there is no supply of sediments to the rill flow with its high transport capacity. It should be noted that the effect of ESP on soil losses from treatments exposed to DW mist is highly significant. iii) Soil losses in TW rain are similar to those in DW mist. The main mechanism for soil erosion in TW rain is the rain detachment and interrill erosion. The magnitude of interrill erosion in our soil samples exposed to TW rain was similar to the rill erosion in DW mist.

The interaction between soil dispersibility (as expressed by soil ESP), rain energy, water quality and slope steepness on soil erosion is shown in Table 3. The effect of slope steepness is expressed by the ratio of soil losses at the 35 and 5 percent slopes. Table 3 also presents the slope ratio effect as predicted by the USLE and WEPP equations. It should be noted, however, that the USLE slope factor was developed for longer

slopes (>10 m) and moderate slope steepness (<20%) and is applicablity to our short slope conditions is questionable. In considering the interaction between slope and treatments on soil losses it should be remembered that volume of runoff was about the same for treatments. The following observations can be made:

1) The slope ratio is a function of soil ESP, the electrolyte concentration in the "rain" water, and the drop impact energy. The effect of slope steepness on soil erosion increased as the dispersibility (and erodibility) of the soil increases (Table 3). Similarly, when TW rain was applied, the slope ratio was diminished (Table 3).

2) When the impact of DW raindrops was prevented (DW mist), soil losses at the high slope were much less than those with high energy DW rain. It seems that the supply of sediments by rain detachment (interrill erosion) to the rills is essential for larger soil losses. This conclusion is supported by the shape of the rills. Whereas the rills formed under mist on high ESP soil were deep, relatively narrow with very steep sides, the rills under rain on the same soil were wider and shallower. The impact of drops eroded the sides and interill areas which resulted in wide rills. Under mist, rill erosion only occured significantly in the bottom of the rills.

3) Tap water mist prevented soil losses and rill formation when compared with DW mist even though the volume of runoff was about the same for both treatments. The ability of the flow shear force to detach soil particles from the soil water interface

depends on the potential of soil particles to disperse. When DW is used, soil dispersion is high and low shear forces (as produced by the short slopes in this study) are sufficient to detach and erode the soil. When TW is used, the flow shear forces in short slopes are not enough to detach and erode the soil surface (Table 3).

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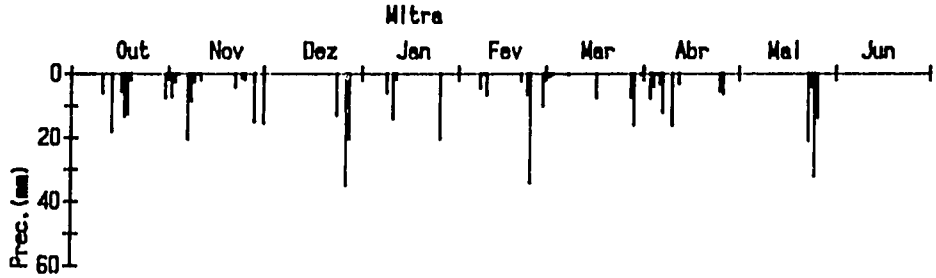
Table 1: Annual precipitation, cumulative runoff and erosion obtained from the plots in the field during the winters of 1988/89 and 1989/90.

Location	Year	Rain	Runoff			Runoff*	Erosion		
			control	PG	mulch		control	PG	mulch
		mm	mm			%	Mg ha^{-1}		
Mitra	1988/89	464	75	71	67	15.5	0.93	0.92	0.70
	1989/90	698	410	370	310	58.7	2.50	1.50	0.50
Alvalade	1988/89	558	110	110	100	19.7	1.05	1.43	0.60
	1989/90	937	130	125	120	13.0	1.71	2.10	1.46
Vale Formoso	1988/89	554	80	58	80	14.4	68.00	58.00	30.00
	1989/90	959	210	140	190	21.9	148.00	146.00	61.00

*Percent runoff out of annual rain for the control treatment.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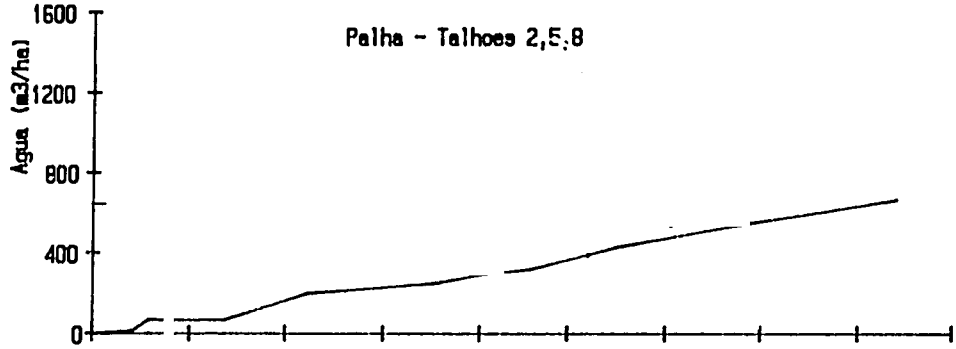
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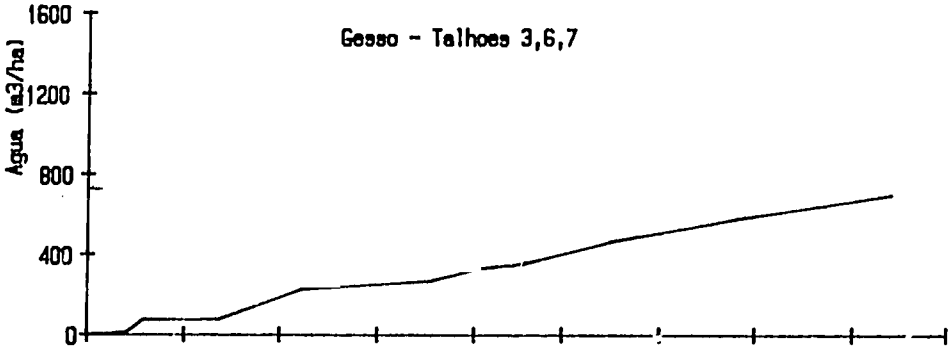
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0
Agua (m3/ha)

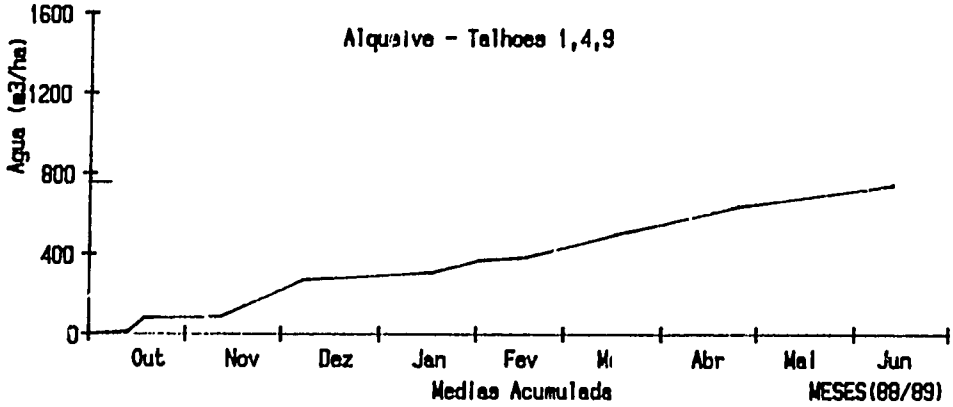

Alquaive - Talhoes 1,4,9
1600
1200
800
400
0
Agua (m3/ha)
Out
Nov
Dez
Jan
Fev
Mi
Abr
Mai
Jun
Medias Acumulada
MESES(88/89)

Fig.

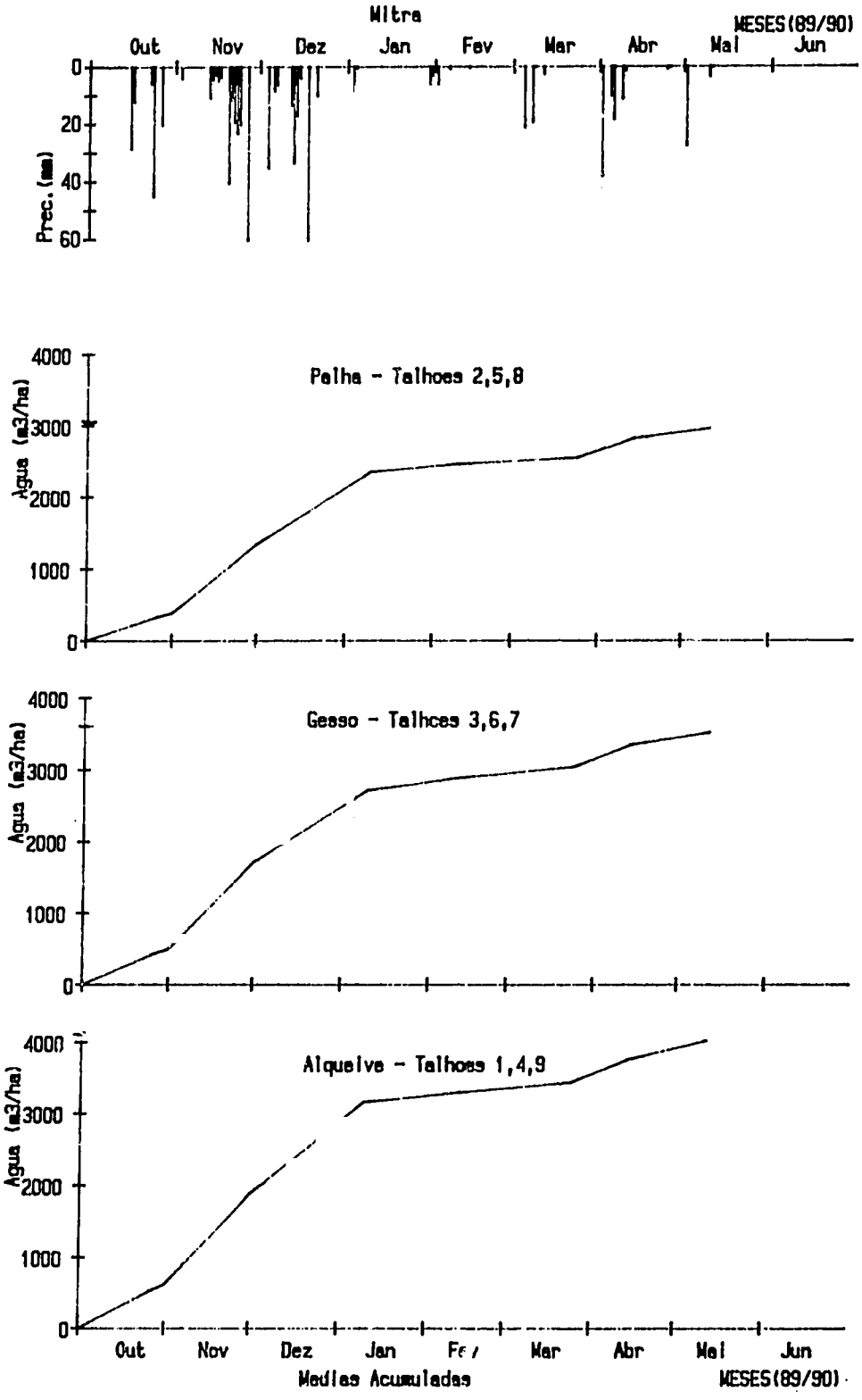

Mitra
MESES(89/90)
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
Prec. (mm)
0
20
40
60
Palha - Talhoes 2,5,8
Agua (m3/ha)
4000
3000
2000
1000
0
Gesso - Talhoes 3,6,7
Agua (m3/ha)
4000
3000
2000
1000
0
Alqueive - Talhoes 1,4,9
Agua (m3/ha)
4000
3000
2000
1000
0
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
Medias Acumuladas
MESES(89/90)

Fig. 2

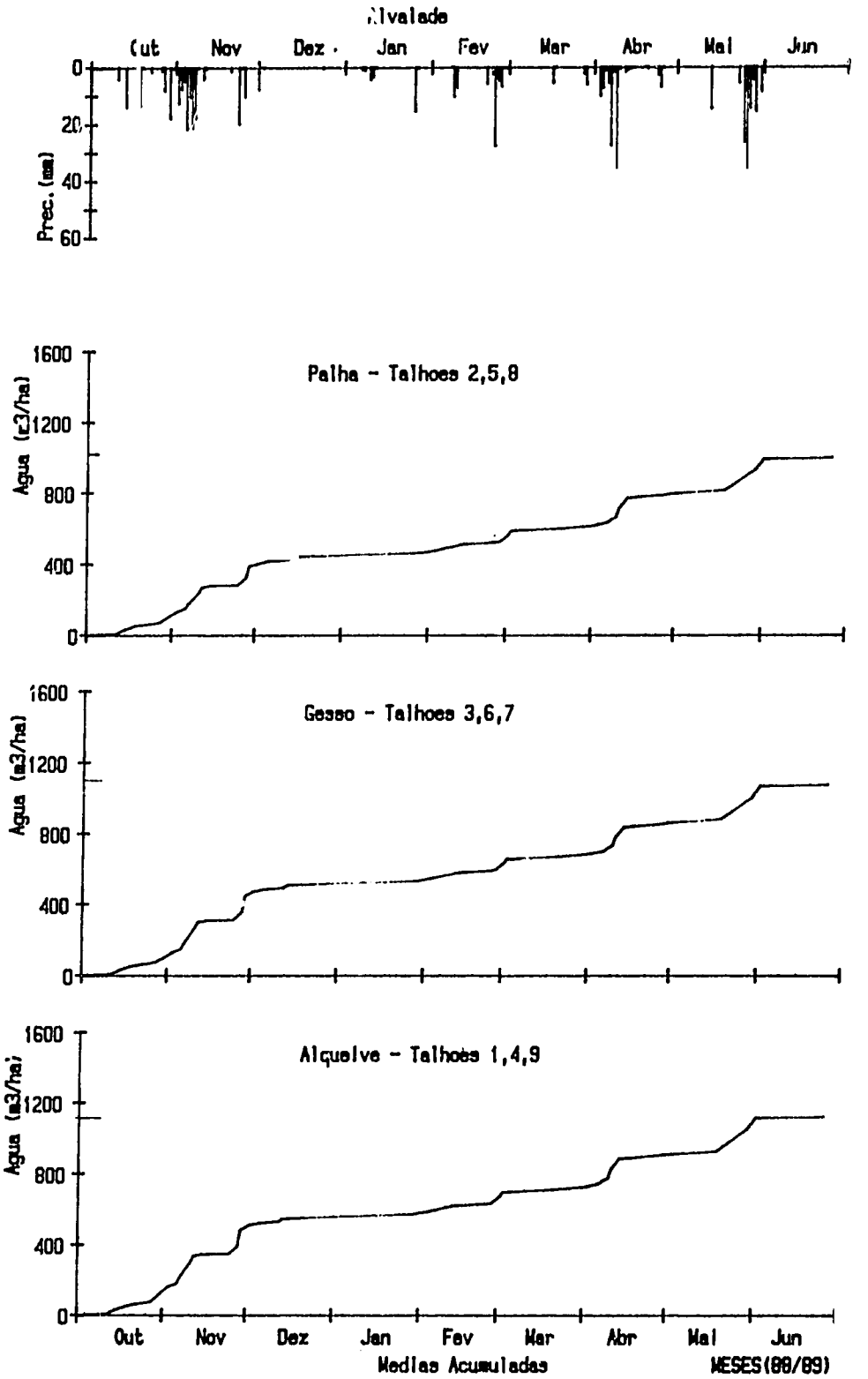

Alvalade
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
Prec. (mm)
0
20
40
60
Palha - Talhoes 2,5,8
Gesso - Talhoes 3,6,7
Alqueive - Talhoes 1,4,9
Agua (m3/ha)
1600
1200
800
400
0
Medias Acumuladas
MESES(88/89)

Fig. 3

115

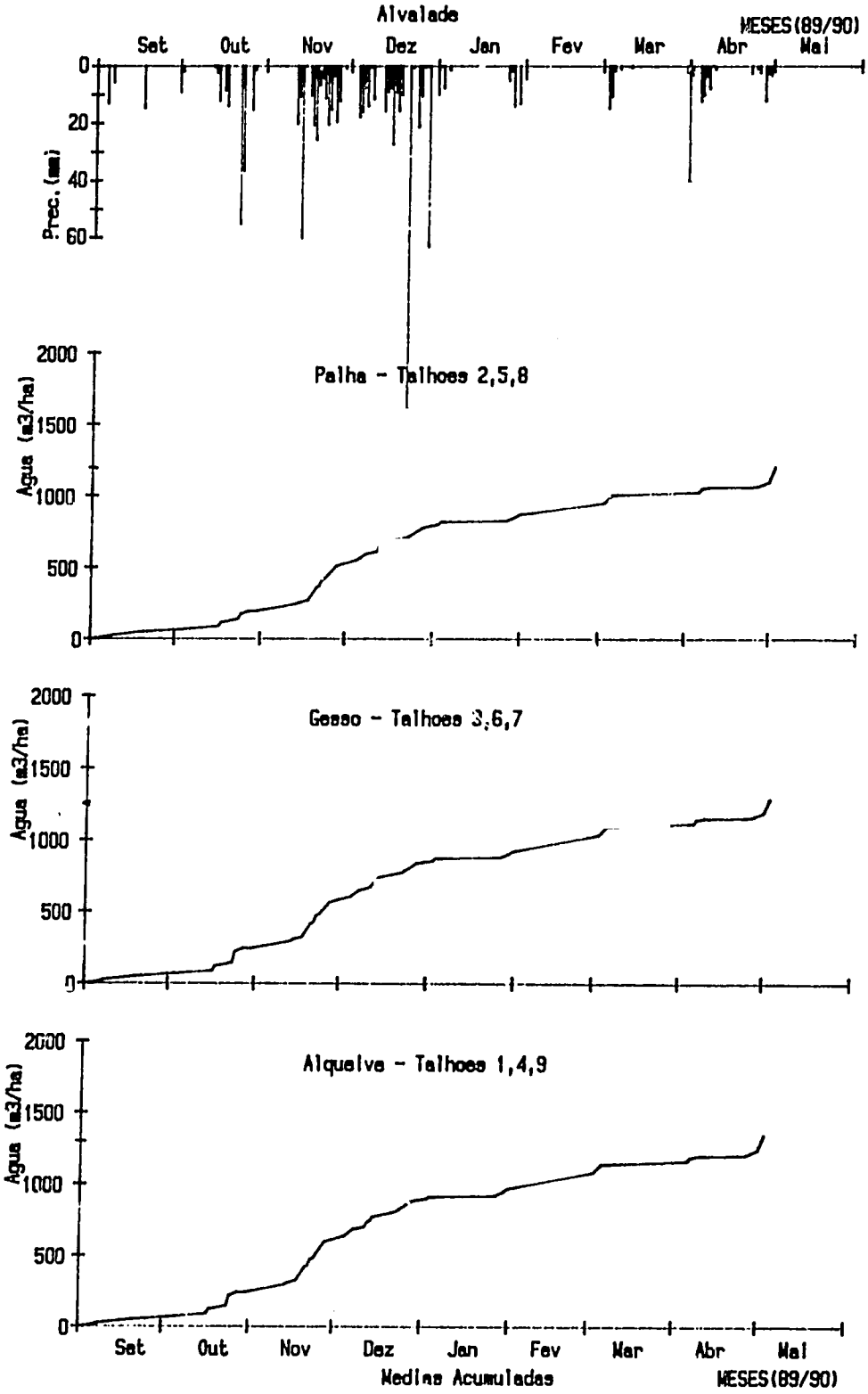

Alvalade
MESES(89/90)
Set
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Prec. (mm)
0
20
40
60
Palha - Talhoes 2,5,8
Gesso - Talhoes 3,6,7
Alqueive - Talhoes 1,4,9
Agua (m3/ha)
2000
1500
1000
500
0
Medias Acumuladas

Fig 18

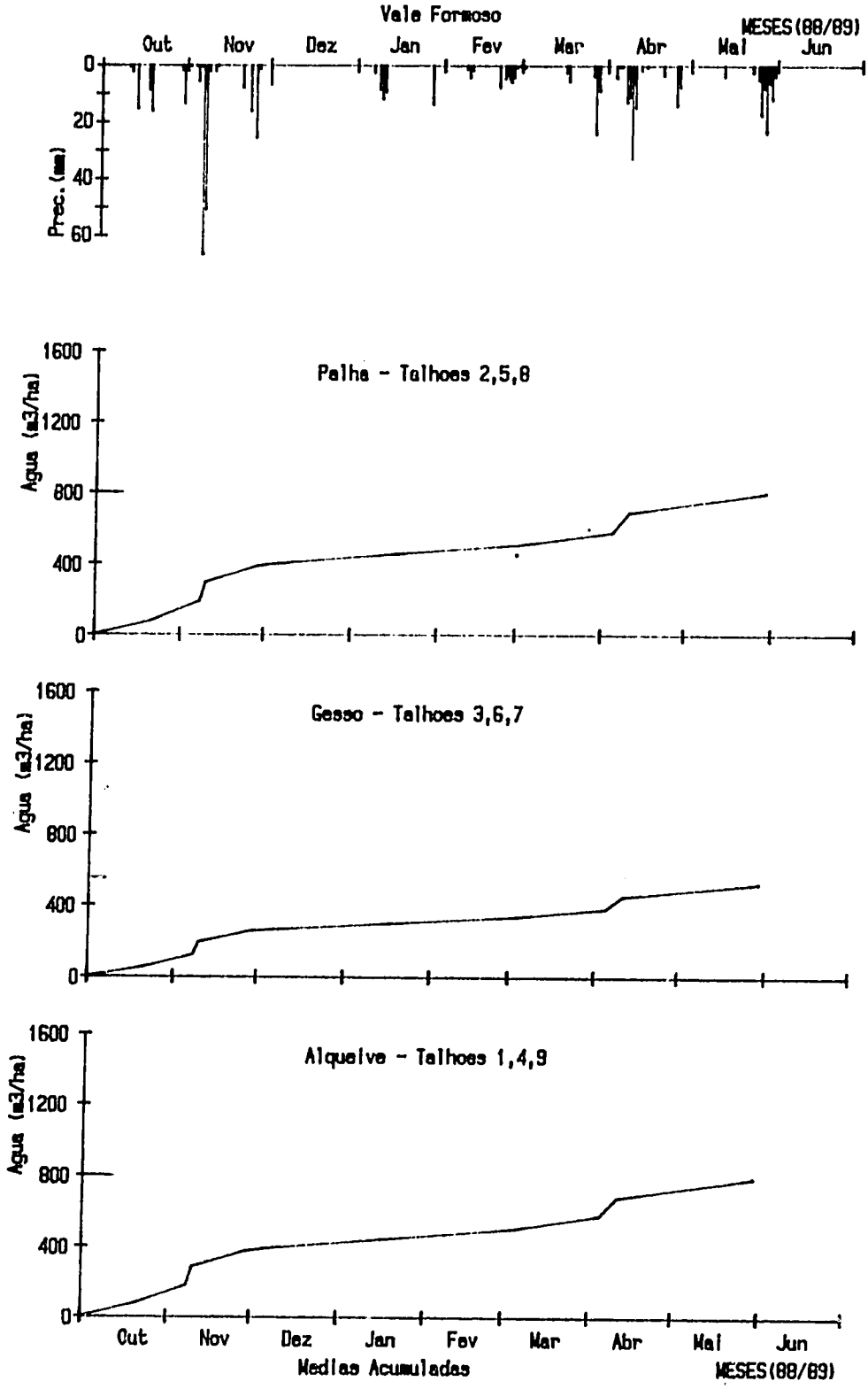
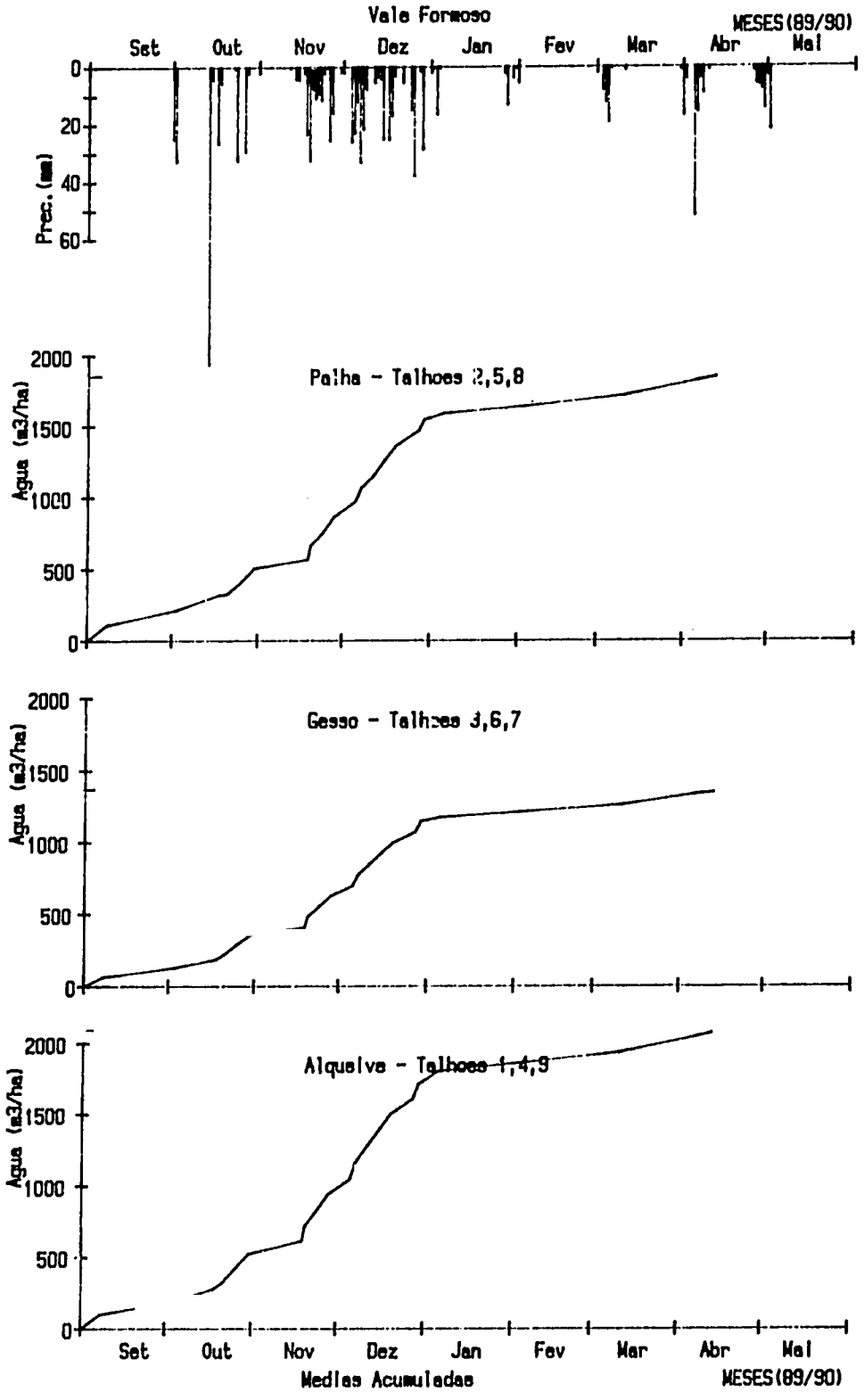

Vale Formoso
MESES(88/89)
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
Prec. (mm)
0
20
40
60
Palha - Talhoes 2,5,8
Gesso - Talhoes 3,6,7
Alqueive - Talhoes 1,4,9
Agua (m3/ha)
1600
1200
800
400
0
Medias Acumuladas

Fig. 5

117


Vale Formoso
MESES(89/90)
Set
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Prec. (mm)
0
20
40
60
Palha - Talhoes 2,5,8
Gesso - Talhoes 3,6,7
Alqueiva - Talhoes 1,4,9
Agua (m3/ha)
2000
1500
1000
500
0
Medias Acumuladas

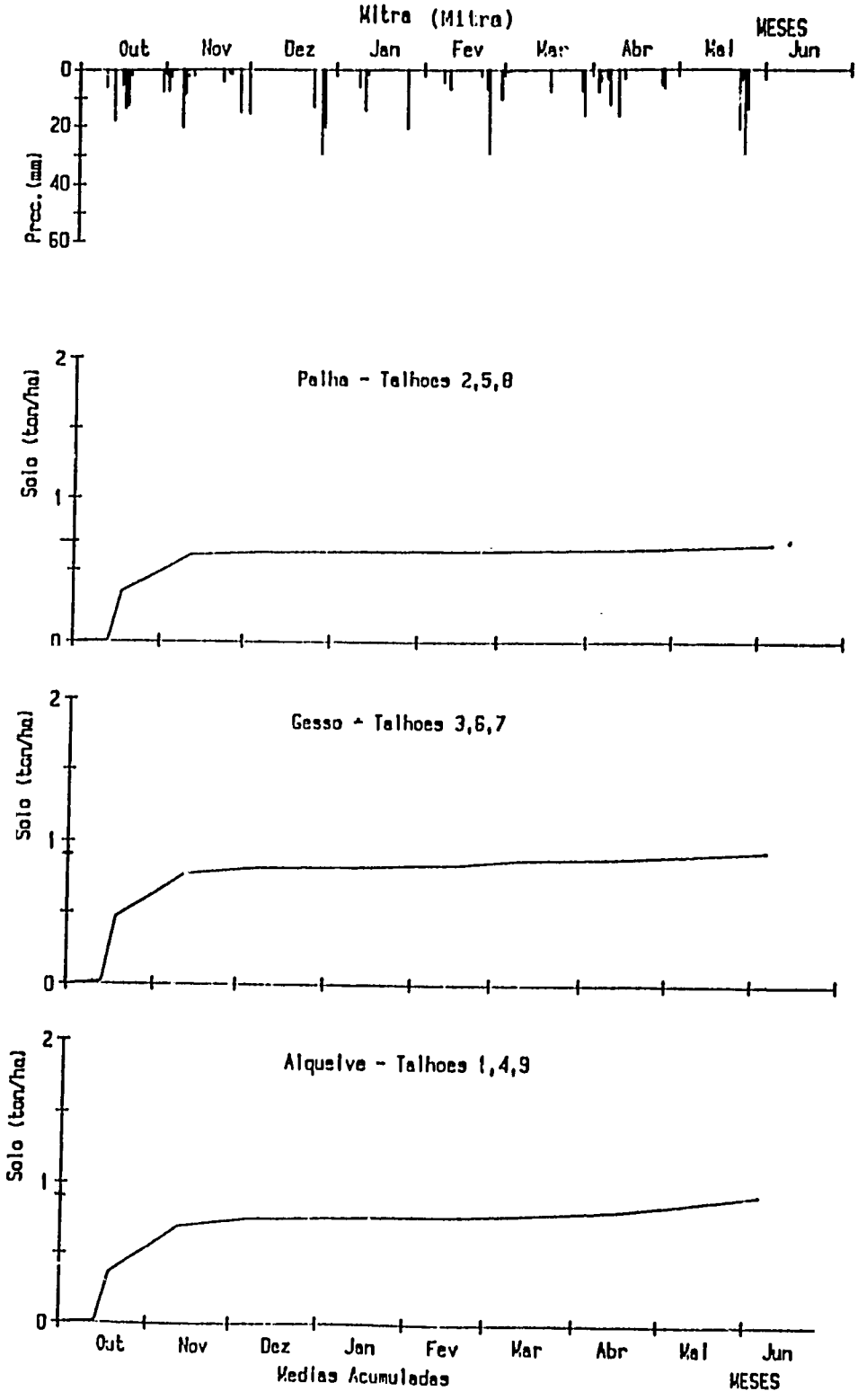
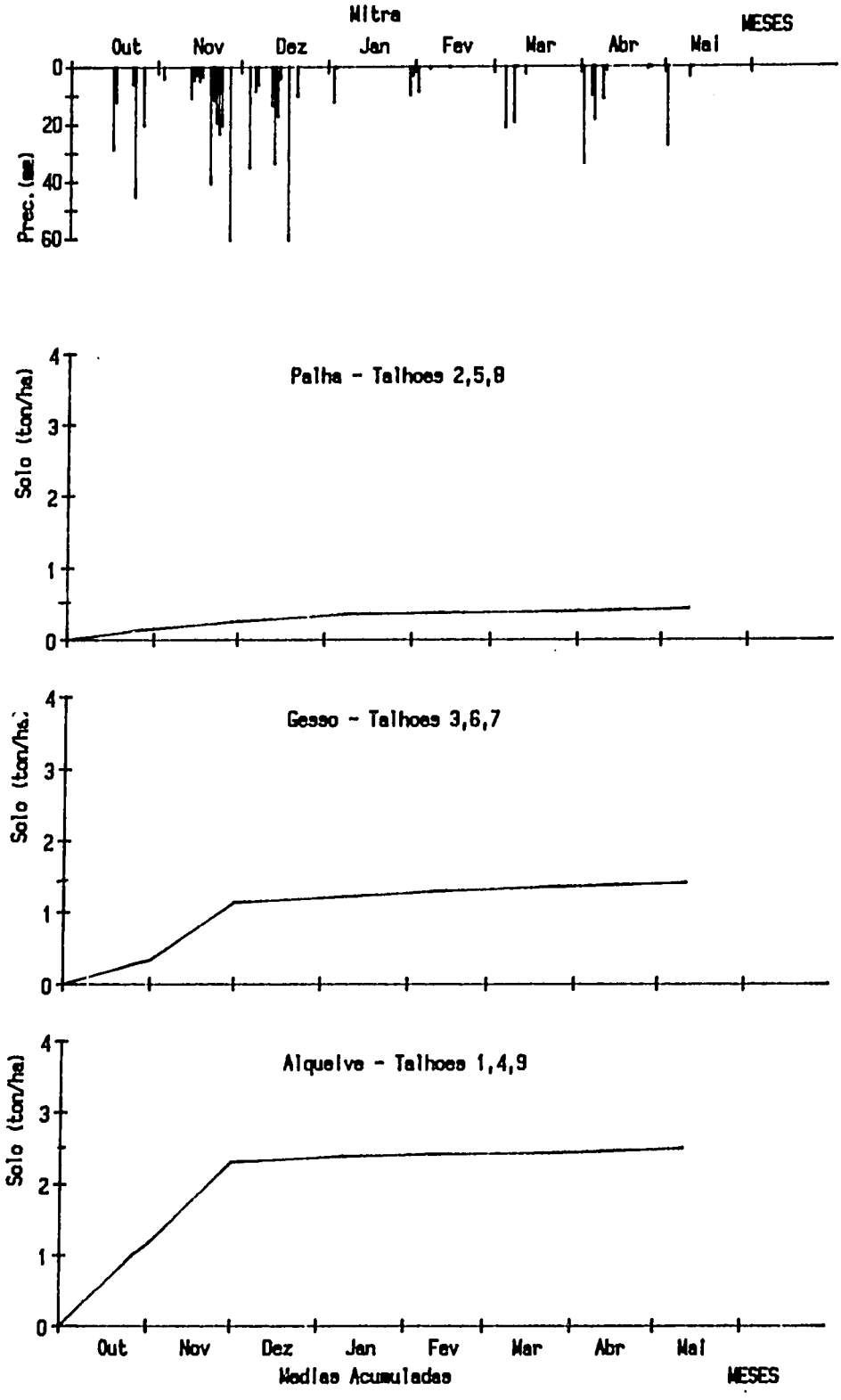

Mitra (Mitra)
MESES
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
0
20
40
60
Prec. (mm)
Palha - Talhoes 2,5,8
Solo (ton/ha)
2
1
0
Gesso - Talhoes 3,6,7
Solo (ton/ha)
2
1
0
Alquelve - Talhoes 1,4,9
Solo (ton/ha)
2
1
0
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
Medias Acumuladas
MESES

Fig.7

(Fig. 15)


Mitra
MESES
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Prec. (mm)
0
20
40
60
Palha - Talhoes 2,5,8
Solo (ton/ha)
4
3
2
1
0
Gesso - Talhoes 3,6,7
Solo (ton/ha)
Alqueive - Talhoes 1,4,9
Solo (ton/ha)
Medias Acumuladas
MESES

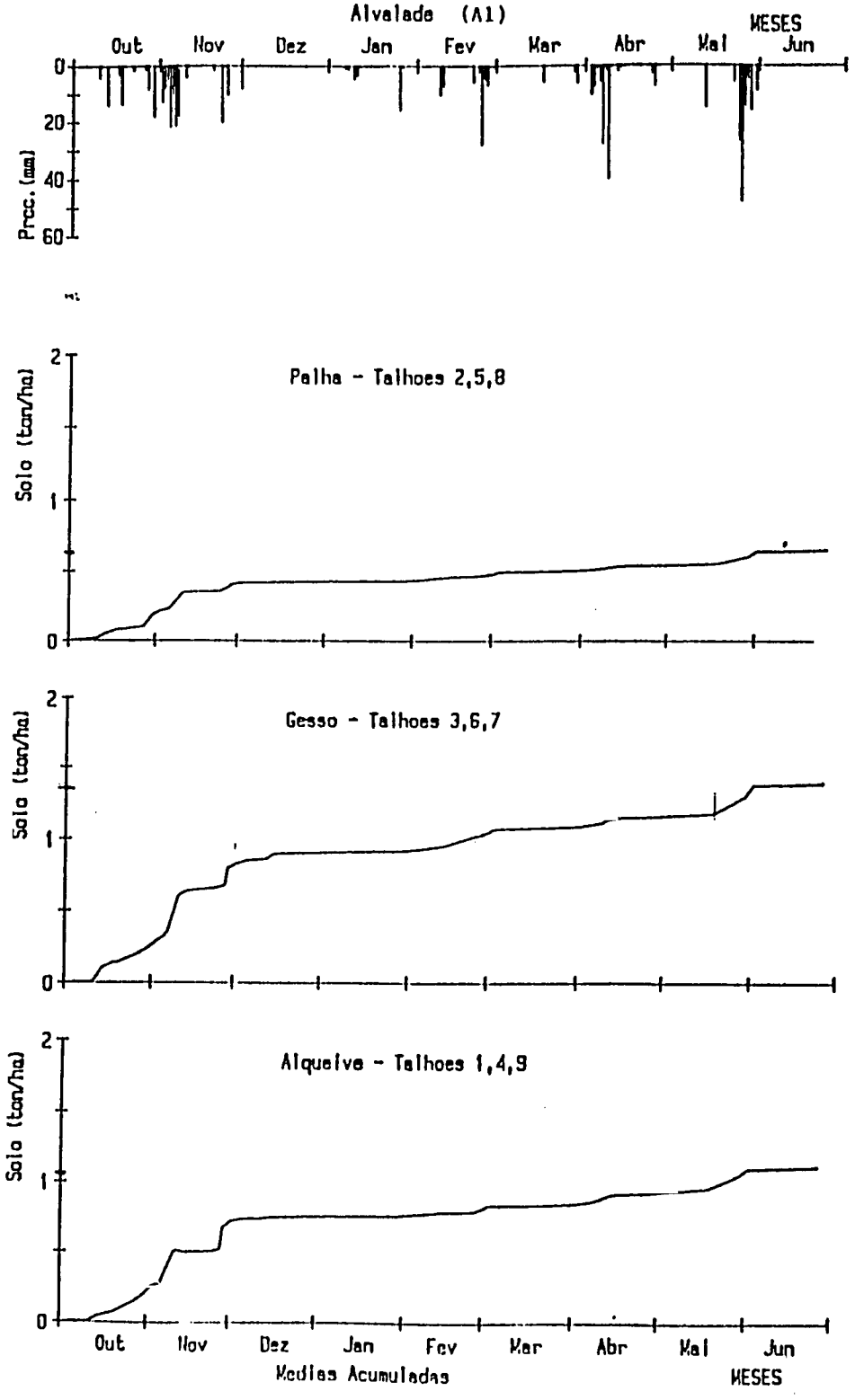
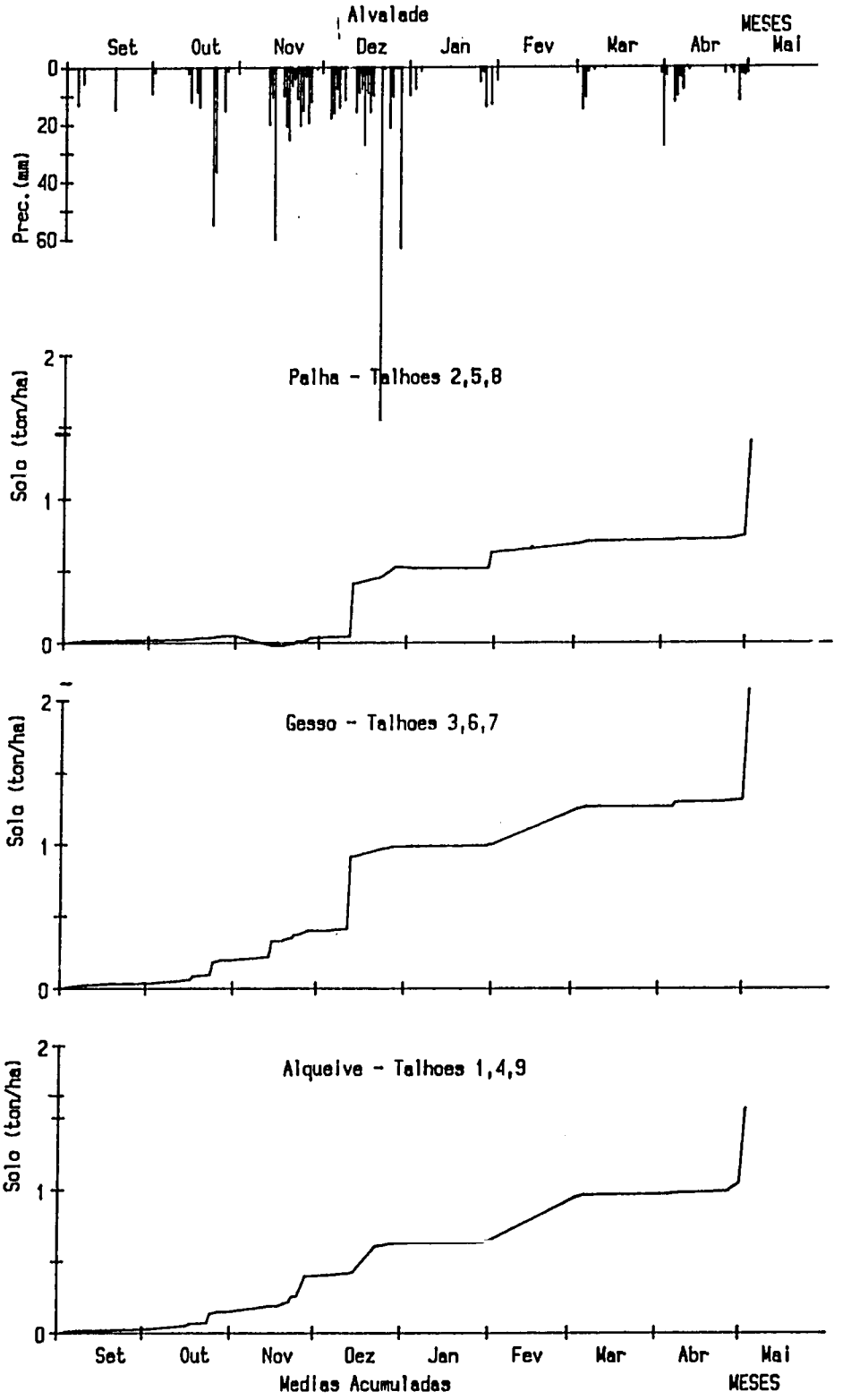


Fig. 3

(Fig. 16)

121


Alvalade
MESES
Set
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Prec. (mm)
0
20
40
60
Palha - Talhoes 2,5,8
Solo (ton/ha)
2
1
0
Gesso - Talhoes 3,6,7
Solo (ton/ha)
2
1
0
Alqueive - Talhoes 1,4,9
Solo (ton/ha)
2
1
0
Set
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Medias Acumuladas
MESES

122

88/89

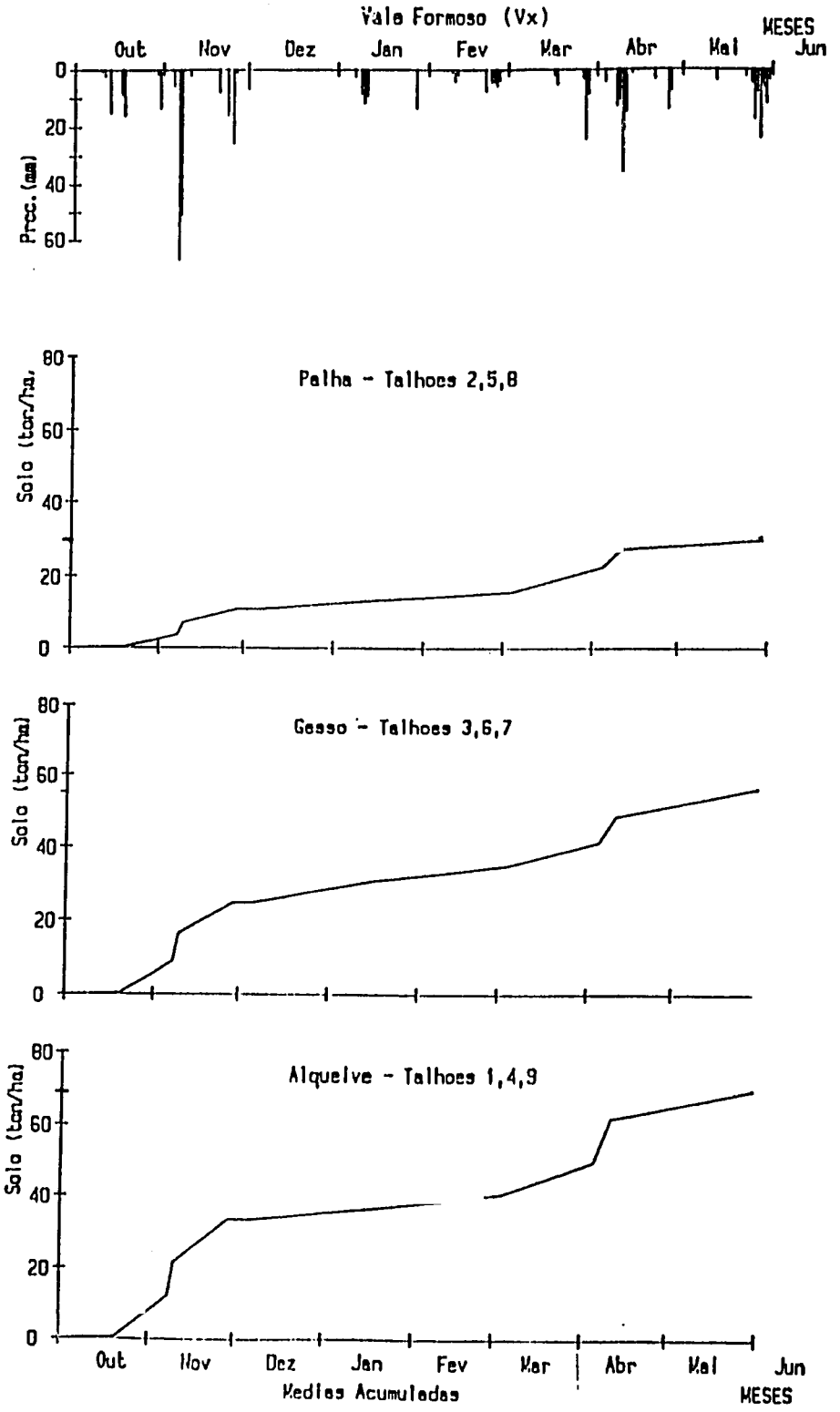


Fig. 11

(Fig. 14)

13

89/90

89/90

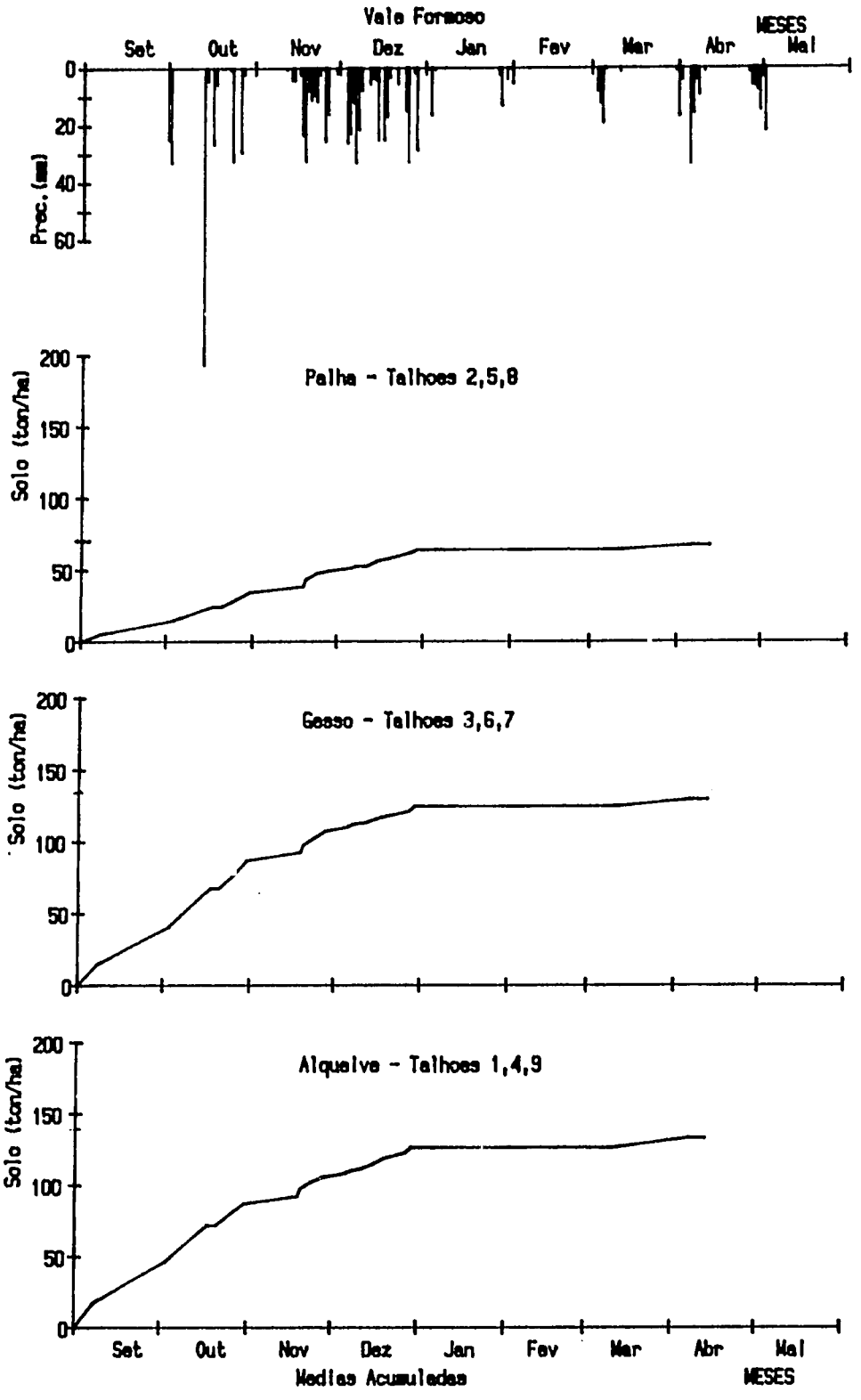
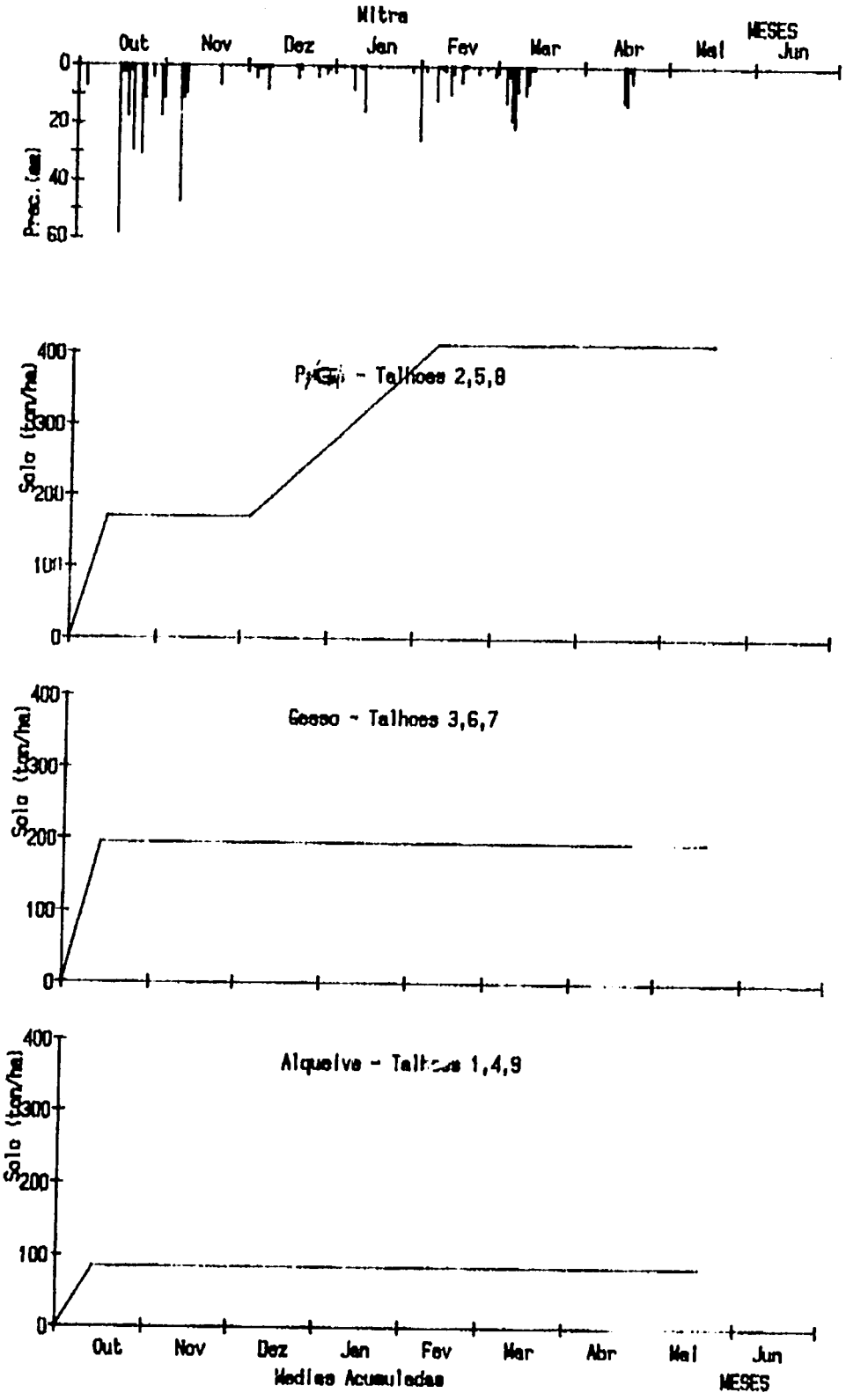
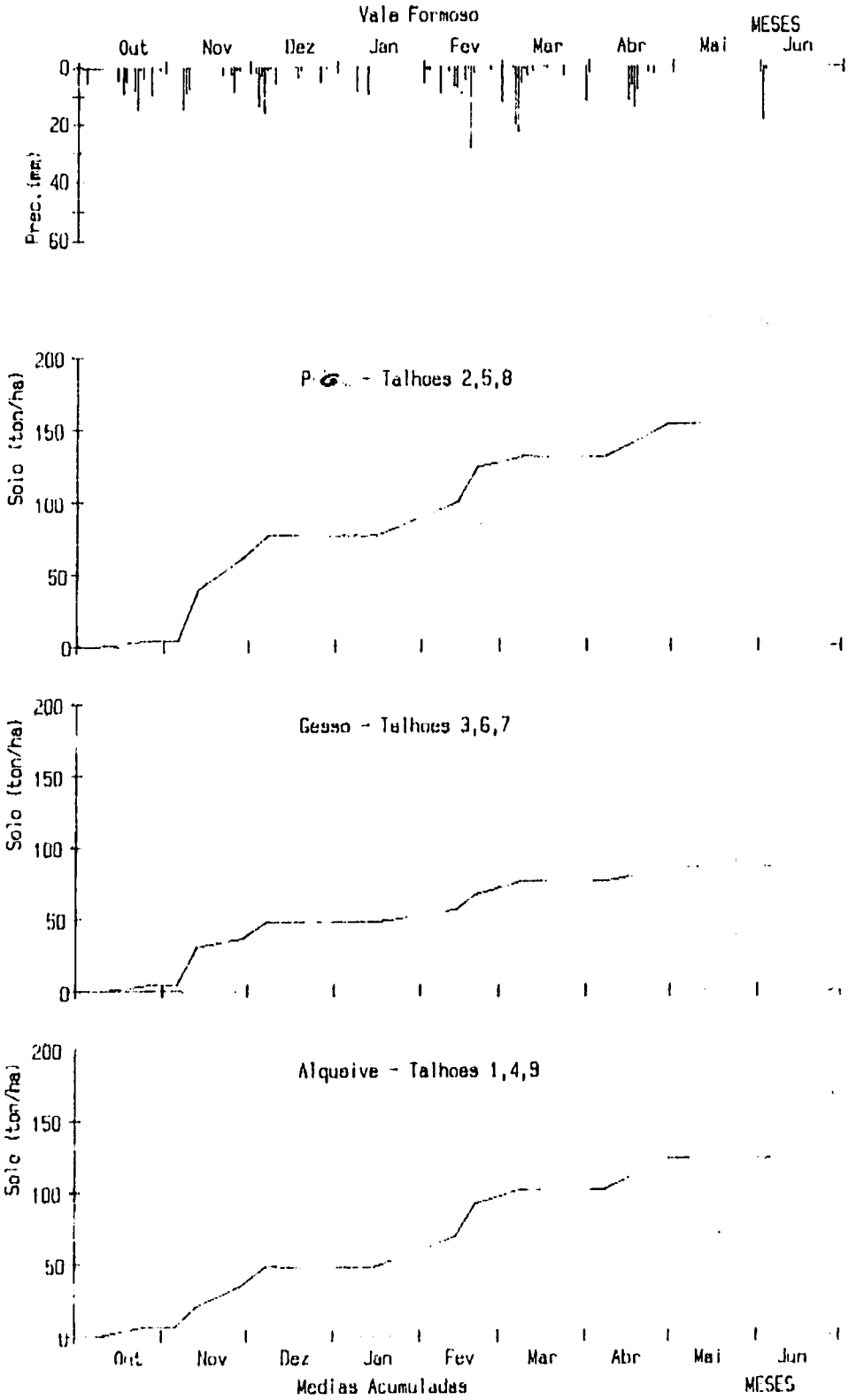


Fig. 12


Mitra
MESES
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
Prec. (mm)
0
20
40
60
Solo (tom/ha)
400
300
200
100
0
Gesso - Talhoes 3,6,7
Alqueive - Talhoes 1,4,9
Medias Acumuladas

125


Vale Formoso
MESES
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
Prec. (mm)
0
20
40
60
Solo (ton/ha)
200
150
100
50
0
P.G. - Talhoes 2,5,8
Gesso - Talhoes 3,6,7
Alqueive - Talhoes 1,4,9
Medias Acumuladas

126

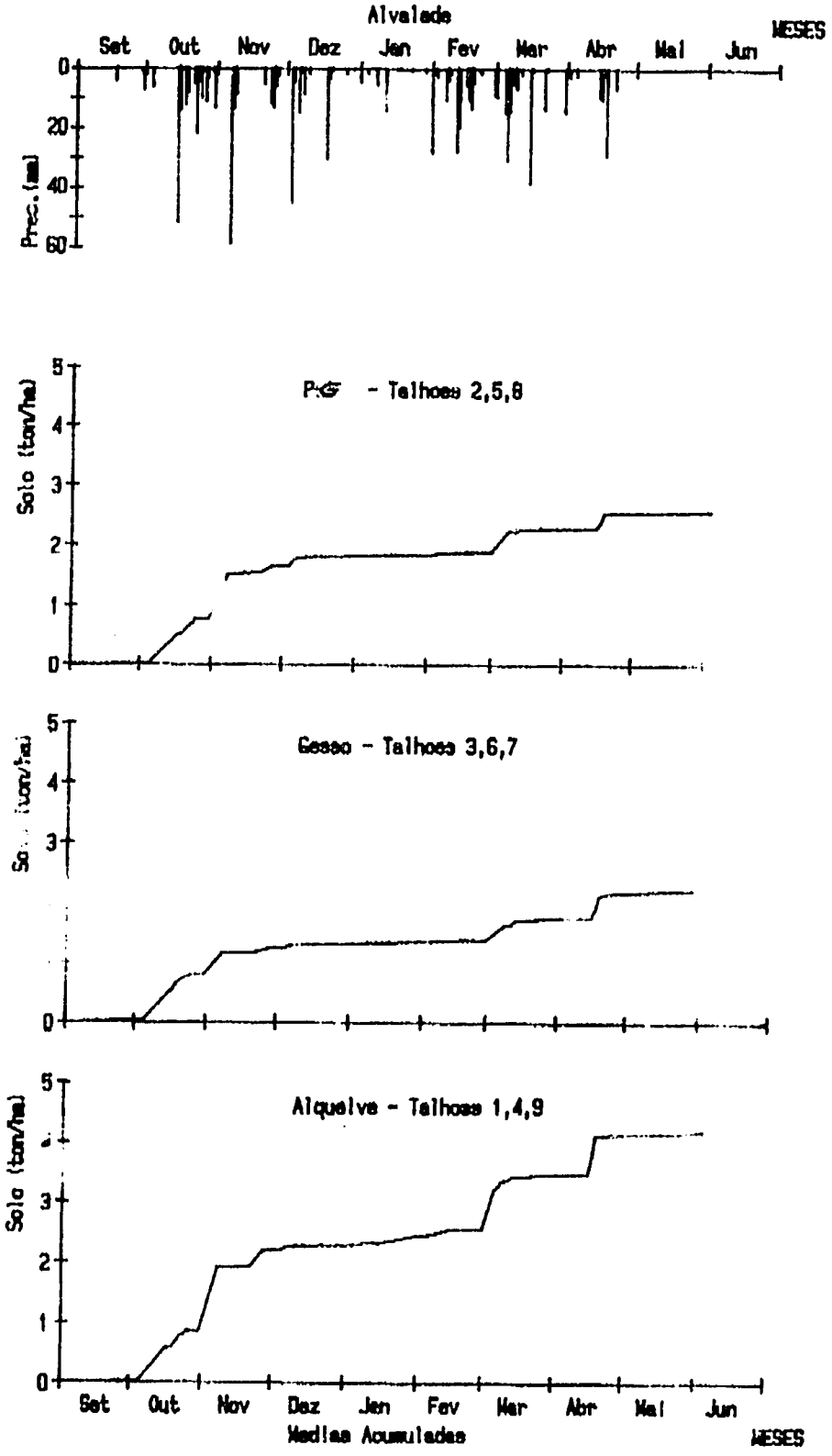

Alvalade
MESES
Set
Out
Nov
Dez
Jan
Fev
Mar
Abr
Mai
Jun
0
20
40
60
Prec. (mm)
5
4
3
2
1
0
Solo (ton/ha)
P.G - Talhoes 2,5,8
Gesso - Talhoes 3,6,7
Alqueive - Talhoes 1,4,9
Medias Acumuladas

Fig. 8