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THE USE OF PHOSPHOGYPSUM AS AN AMELIORANT FOR POORLY STRUCTURED CRUST-FORMING SOILS

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Abstract

Surface crusting under raindrop impact reduces rainfall efficiency, increasing drought stress already associated with poor soils. An amelioration project was undertaken using both field and laboratory rainfall simulators. The field study, conducted on a Longlands form soil of low exchangeable sodium percentage (ESP 3,5), compared two rates of phosphogypsum (PG 2,5 t/ha, 5 t/ha) in combination with scattered tops (ST). PG improved infiltration rate (IR) and reduced runoff, although less effectively than a trash blanket. Runoff volumes, when compared with the control treatment, were reduced by 46%, 55% and 79% for the ST, ST + 2,5 t PG/ha and ST + 5 t PG/ha respectively. Soil losses were also significantly lower. Laboratory simulation compared soils of variable ESP with and without 5 t PG/ha. As ESP increased, final IR decreased. PG improved final IR by 20% on soil with a low ESP (3,5) and by 56% on soil with a high ESP (17,7). PG prevented a rapid decline in IR, reduced crust formation and improved rainfall efficiency. Optimum PG application rates were influenced by soil form and the level of exchangeable sodium present.

Introduction

Most of the grey duplex soils of the Glenrosa, Swartland, Westleigh, Longlands and Kroonstad forms derived from Middle Ecca, Dwyka and Beaufort sediments are prone to erosion due to low water intake rates, high runoff rates and shallow profiles. The susceptibility of these soils to erosion and waterlogging during wet seasons and drought stress during dry periods, is increased by the development of a surface crust, which reduces rainfall efficiency.

Physical disaggregation of soil particles occurs in response to the impact of raindrops, causing compaction of the surface layer which limits water penetration into the soil (Ben Hur *et al*[2]; Morin *et al*[11]). This physical breakdown occurs where very little sodium exists in the exchange complex or where the soil surface solution has an electrolyte concentration too low to maintain physical structure during raindrop impact (Kazman *et al*6; Shainberg *et al*[13]). Chemical dispersion of clay particles is influenced by the level of exchangeable sodium in the soil and the salt concentration of the percolating solution. Dispersion results in low surface permeability by clogging pore spaces and available channels for water movement (Agassi *et al*[1]).

Clay mineralogy can greatly influence crust formation (Morin *et al*[11]). Kaolinite appears to be less dispersive than montmorillonite, resulting in a less dense crust of higher permeability and thus higher final infiltration rates. However, kaolinitic soils become more susceptible to crust formation with increasing exchangeable sodium percentage (ESP), particularly when the ESP value exceeds 10 (Frenkel *et al*[4]).

A strong crust does not form when a surface mulch such as trash is provided. The mulch serves to reduce the compacting effect of falling raindrops, and increases the time available for water to infiltrate. From previous studies (Frenkel *et al*[4]; Shainberg *et al*[13]), phosphogypsum (PG) showed promise in reducing soil crusting and runoff losses under simulated rainfall (Dewey *et al*[3]). The ameliorative effect of PG appears to be greatest where high levels of exchangeable sodium are found in the soil, due to its ability to decrease the dispersive effects of sodium on clay minerals. Previous research into the properties of the grey duplex soils has shown them to be very sensitive to excess sodium (Johnston[5]).

Initiation of a research project at the Experiment Station to study the amelioration of crusting, led to a three-phase experiment which resulted in PG being selected as the most suitable ameliorant (Meyer *et al*[9]). Subsequently, a rainfall simulator field trial was conducted to assess the effects of scattered tops in combination with phosphogypsum as a means of improving the quality of weakly structured erodible soils, which would be particularly important in areas where trashing of cane is not recommended. The spreading of burnt tops appears to give about 60% of the protective effect of trash, and it was thought that a combined treatment of PG top-dressed over scattered tops (ST) might improve soil stability and rainfall efficiency as effectively as a trash blanket. Laboratory rainfall simulator tests were carried out to determine the effects of ESP in the soil on crusting in relation to treatment with PG, and to establish whether ESP can be used as a criterion when recommending the use of PG within the sugar industry. Some of the results obtained from the use of PG as an ameliorant for crust-forming soils are presented here.

Experimental procedure

1. Field rainfall simulation trial

The trial was conducted on a Longlands form soil with a history of poor cane growth. The trial site had a 3% slope and showed poor soil physical properties such as low infiltration rate, shallow rooting depth, high erodibility and proneness to crust formation. Some of the soil properties are given in Table 1. The trial comprised the following treatments:

- control - no tops, no phosphogypsum
- scattered tops (ST) - no PG
- ST + 2,5 t PG/ha
- ST + 5,0 t PG/ha

The source of the phosphogypsum ($CaSO_4.2H_2O$; P ± 0,4%, F ± 0,18%) was Richards Bay, where it is a by-product of a phosphoric acid factory. The above treatments were replicated twice. PG was applied on the soil surface one day before simulating a storm. Two 60 minute storms were applied on consecutive days (i.e. one storm on a dry profile, followed by another within 24 hours on the wetted profile) at an intensity of 63 mm/hr. The water used had an electrical conductivity value of 20 mS/m and an SAR value of 0,03. A rotating-boom rainfall simulator was used, and was found to have a coefficient of rainfall uniformity of 94% (Platford[12]). Plots were of a standard size (10,7 m × 1,8 m) and runoff and sediment samples were taken at three minute intervals during the storms.

2. *Laboratory rainfall simulation tests*

Bulk topsoil samples (0 - 100 mm) were taken, representative of Longlands, Kroonstad and Rensburg form soils, varying widely in ESP and clay type (see Table 1). The soils were sent to the Soils and Irrigation Research Institute, Pretoria, where a rotating-disc laboratory rainfall simulator (Morin *et al*[10]) was used to assess the effect of PG on crusting and intake rates. Rainfall application, using distilled water, continued for 60 minutes (or until constant runoff was achieved) at 45mm/hr intensity. The treatments were as follows:

Low ESP (3,5)	Moderate ESP (10,1)	High ESP (17,7)
Control	Control	Control
PG at 5 t/ha	PG at 5 t/ha	PG at 5 t/ha

Note: All PG treatments were applied to the soil surface.

3. *Laboratory measurements*

Various measurements were made on the surface crust samples, including:

- particle size analysis using the hydrometer method
- clay minerology by X-ray diffraction
- soil chemical measurements
- dispersion percentage, as a measure of aggregate stability
- permeameter studies using the method described by Johnston[5].

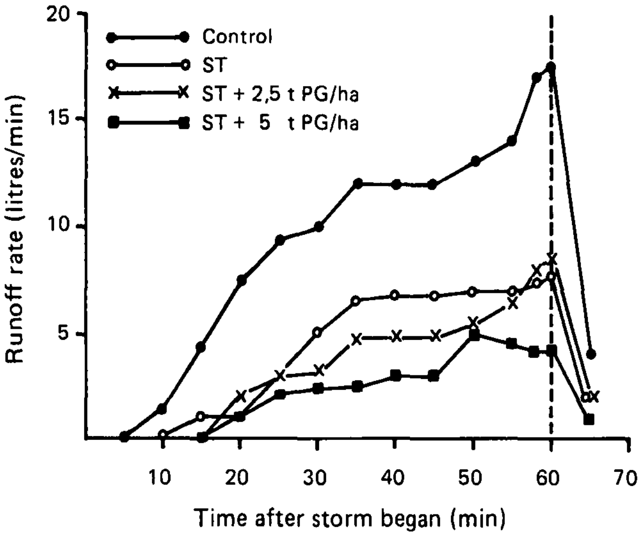

FIGURE 1 Variations in runoff rates during storm 1.

Results

1. *Field simulation results*

1.1 *Runoff curves for storms 1 and 2*

Figure 1 shows the runoff curves for the four treatments, during the first storm, on a dry profile. There was a time lapse of 6 minutes between the start of simulation and initial runoff in the control treatment, while in the ST treatment infiltration occurred for 11,5 minutes before runoff commenced.

Infiltration in both the ST + PG treatments occurred for more than 15 minutes before any runoff was monitored. Once runoff began, the control treatment showed a rapid increase in the rate of water loss, with a final rate of 17 l/min. As the application rate was 24,2 l/min for storm 1, the final runoff rate comprised 70% of the total rainfall being applied. Final runoff rates were 39%, 35% and 24% of total rain applied for the ST, ST + 2,5 t PG/ha and ST + 5,0 t PG/ha treatments respectively.

Runoff rate in the control treatment during the second storm (figure 2) reached 80% of the rainfall being applied after only 11 minutes; comparable runoff rates for treatments 2, 3 and 4 were reached only after 17, 19 and 22 minutes respectively. For all treatments, final runoff rates were at least 30% higher in the second storm compared with the first.

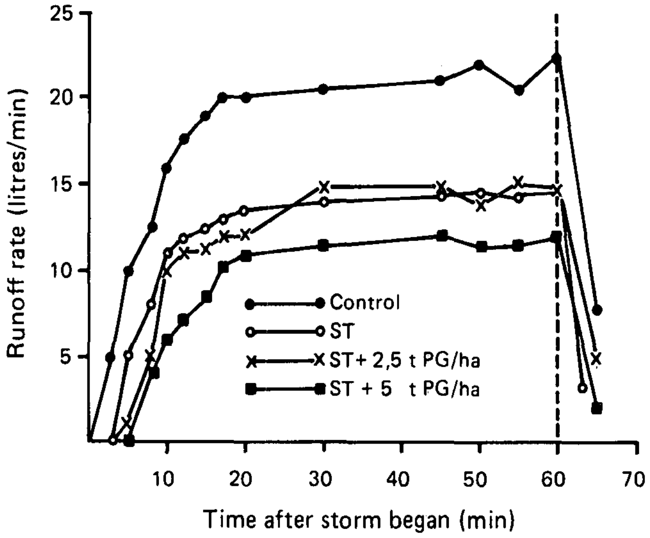

FIGURE 2 Variations in runoff rates during storm 2.

1.2 *Total runoff volumes for storms 1 and 2*

The total volume of water lost during storm 1 also indicated that the ST treatments were beneficial in improving rainfall efficiency. Total runoff, expressed as a percentage of total rainfall, was 42% greater in the control treatment than that from the ST treatment (24%) (Figure 3). In the presence

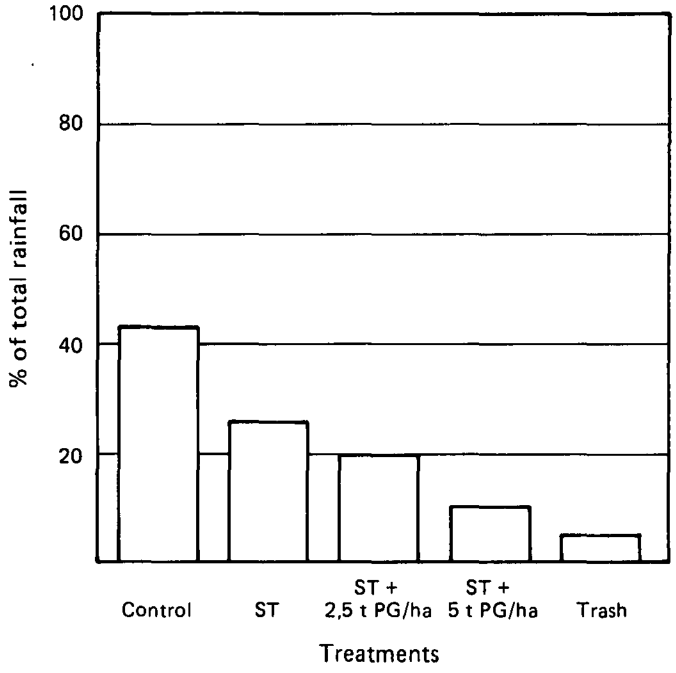

FIGURE 3 Proportions of rainfall lost as runoff in storm 1.

of PG, total runoff volumes were 20% and 10% of total rainfall applied for the ST + 2,5 t PG/ha and ST + 5 t PG/ha treatments respectively. The low runoff value for the ST + 5 t PG/ha treatment compared favourably with the total runoff value when a trash cover was used. This had been determined in a previous trial. It was 5% of rainfall applied, illustrating the excellent cover offered by a dense layer of organic material (Meyer *et al*[9]).

The total volume of water lost in the second storm was generally greater than that in the first storm for all the treatments. In terms of residual treatment effects, runoff volumes declined in the following order: control > ST > ST + 2,5 t PG/ha > ST + 5 t PG/ha. In general, the residual effect of the ST treatment was still marked but not greater than that of the PG treatments. In the control treatment, total runoff volume was 92% of the rainfall applied (figure 4) so that almost all the rainfall applied (63 mm) was lost. Total runoff volumes were far lower in the other three treatments, the least being 44% of rainfall applied to the ST + 5 t PG/ha treatment, which was less than half that lost from the control treatment. Runoff from the previously trashed treatment was only 22% of the total rainfall applied.

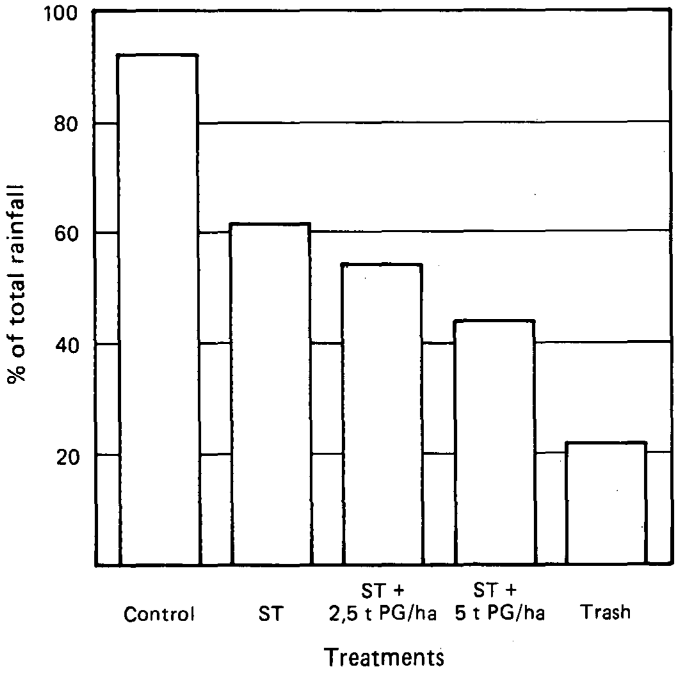

FIGURE 4 Proportions of rainfall lost as runoff in storm 2.

1.3 *Total soil losses from storms 1 and 2*

Soil loss was measured by calculating the sediment load (g) in each of the runoff samples, expressed as t/ha. Figure 5 gives a comparison of the total sediment loss from the four treatments for storm 1. The control treatment with no cover lost the greatest amount of soil (2,6 t/ha). Soil loss from this treatment was 75% higher than that from the ST treatment. The two PG treatments appeared to have little effect in reducing soil loss below that from the ST treatment. The sediment load from the previous trash treatment was only 13% of that from the control treatment and the loss remained at this low level throughout storm 1 (figure 5).

During the second storm soil loss from the control treatment (figure 6) was more than double that lost during the first storm. The total mass of sediment measured from this treatment rose by 2,9 t/ha from 2,4 t/ha to 5,3 t/ha. However, in the ST treament, soil loss increased by only 1 t/ha, when compared with the control treatment. Again, the ST + 2,5 t PG/ha treatment appeared to have little effect in reducing soil loss, although the higher rate of PG application reduced soil loss by 20% when compared with the ST treatment.

Previously trashed treatments showed soil losses which were 94% lower than those from the control treatment and 79% lower than scattered tops combined with the higher PG rate (5 t/ha).

2. *Laboratory simulation results*

Topsoils of varying ESP values were selected to test the effect of ESP on crust formation and soil and water losses under simulated rainfall. The results of the laboratory simulation are expressed as infiltration rate (IR; mm/hr) as a function of cumulative rainfall. The initial IR was similar for soils at all ESP values at the onset of rainfall. In the control treatment of high ESP (17,7; figure 7), there was a

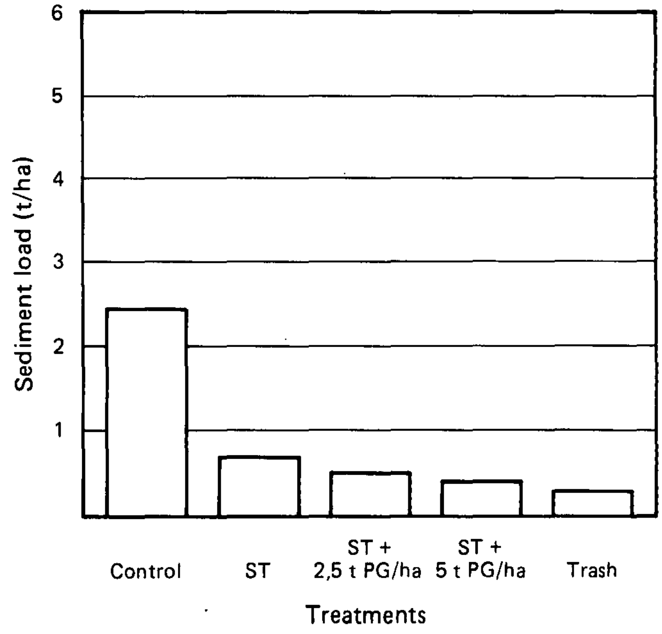

FIGURE 5 Amounts of soil lost in runoff in storm 1.

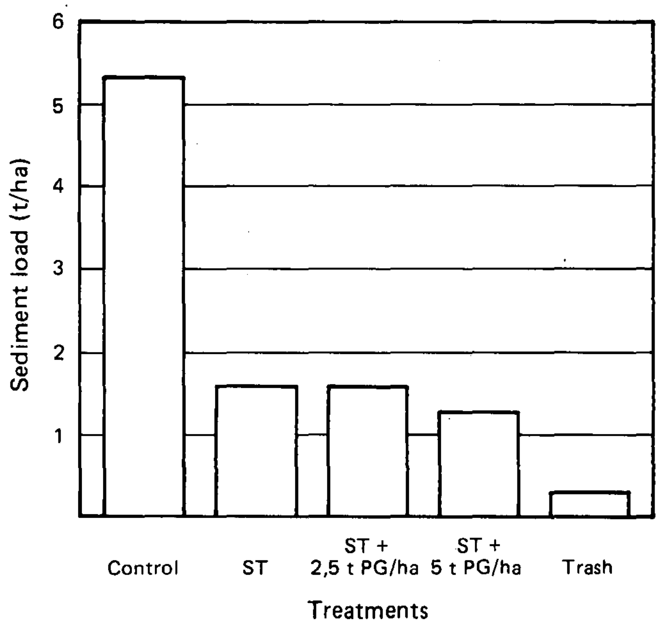

FIGURE 6 Amounts of soil lost in runoff in storm 2.

sharp decline in IR and the final infiltration rate (FIR) of only 3 mm/hr was achieved after 22 mm of rainfall. The total amount of water infiltrating was much less when compared with the soils of lower ESP. At lower ESP values, the IR remained higher, decline in IR was slower and the FIR more than doubled (6 mm/hr at ESP 10,1 and 11 mm/hr at ESP 3,5).

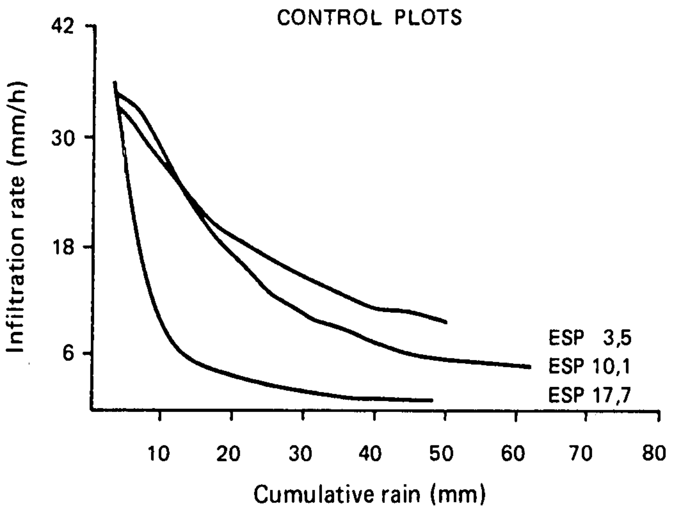

FIGURE 7 Infiltration rates for three soils with different ESP values.

In the soil of low ESP (3,5) a far slower decline in IR was noted (figure 8) in the presence of 5 tPG/ha and the FIR was higher than in the control sample of the same ESP. Whereas the FIR of the control sample after 50 mm rain was only 11 mm/hr, the FIR of the sample treated with PG had improved by 27% to 14 mm/hr. Initial infiltration rates in the soil of moderate ESP (10,1) were slightly higher (38 mm/hr). The control treatment showed a rapid decline in IR, the final IR of 5,5 mm/hr being reached after 45 mm of rain. Where PG was applied, the decline in IR was far slower and the FIR, which was three times that of the control (15 mm/hr), was reached only after 58 mm of rain.

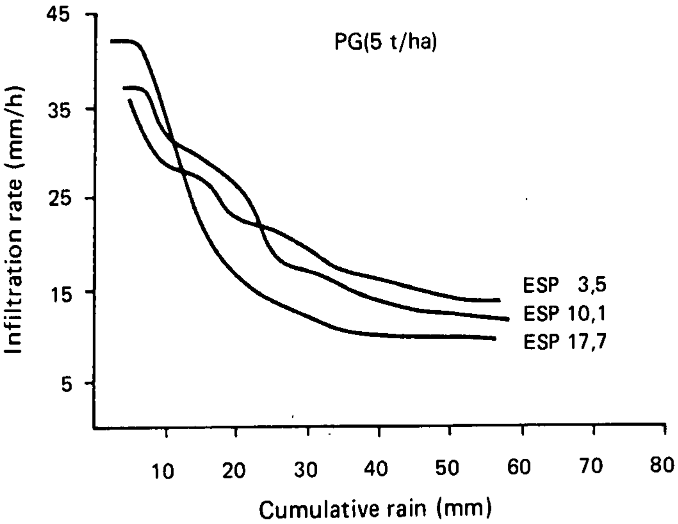

FIGURE 8 Effect of PG on intake rate of three soils with different ESP values

The decline in IR was most marked in the soil of high ESP (17,7) where the FIR of 3 mm/hr was reached after only 22 mm of rainfall, less than half the applied storm. Crust formation occurred early in the storm and resulted in almost total sealing of the soil surface. Where PG had been applied, 95% of rainfall infiltrated for more than eight minutes prior to decline in IR, 56% more than in the control treatment. FIR was reached only after 35 mm, or when 70% of rainfall had been applied. FIR was also four times higher (12 mm/hr) than that of the control plot (3 mm/hr).

3. Laboratory measurements

Measurements, including dispersion percentage and hydraulic conductivity, using brass permeameters were made before and after the storm. In the soil of high ESP (17,7) which had a clay content of 43%, the dispersion value was 62%, while in the soils of moderate and low ESP, dispersion values were 24% and 22% respectively. After the storm had been applied, the dispersion values rose for soils with low and moderate ESP values. The value for the high ESP soils was not measured. The dispersion percentage of the soil of moderate ESP increased to 55% after storm application. The chemical effect of a higher initial electrolyte concentration in the surface soil solution (EC ± 180 mS/m) in addition to the application of further electrolytes from the dissolution of PG resulted in an electrolyte concentration high enough to overcome the dispersive effects of the higher ESP. This was particularly noticeable at the higher rate of PG application. However, in the soil of low ESP, the effect of sodium and an initial low EC (40 mS/m) resulted in physical disaggregation and increased dispersion even in the presence of PG. The rate of PG applied was not enough to raise the electrolyte concentration sufficiently high to overcome the dispersive effects of ESP. The susceptibility to dispersion under raindrop impact increased with increasing ESP and lower initial electrolyte concentration. These results support the relationship described by Loveday[8] who attributed the beneficial effect of PG in lowering dispersion to an increase in salt concentration rather than a reduced sodium level.

The hydraulic conductivity curves for three samples treated with varying rates of PG are given in Figure 9. The average HC of the untreated soil (ESP = 10) was 7 mm/hr. The lower rate of PG improved the HC to 12 mm/hr. The highest HC

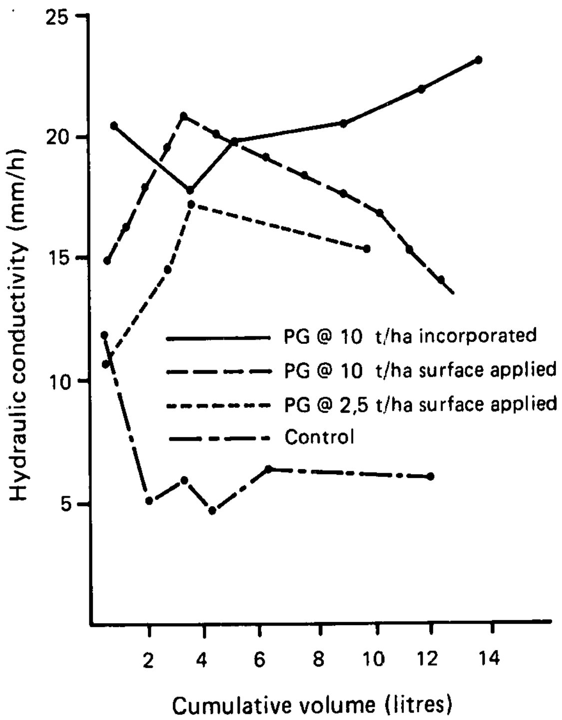

FIGURE 9 Hydraulic conductivity of samples treated with different amounts of PG.

was reached when 10 t PG/ha were applied, raising the electrolyte concentration of the soil solution above the threshold value, thus reducing the dispersive effect of the high ESP value. Reasonable soil HC can thus be maintained, even at higher ESP values, provided the EC of the applied water remains at a level high enough to overcome the effects of sodium.

A hand penetrometer was used to monitor the development of a surface crust after a storm. The pressure applied to the soil surface was compared with the depth of the compacted crust to give an index of the crusting peak (CP). The crust was found to be stronger and thicker in the control treatment (CP = 7,9) than where PG had been applied (CP = 4,9). The CP value was even lower where trash had been applied (CP = 4,6), indicating that crust formation was limited where the energy of raindrops was dissipated before reaching the soil surface.

Table 1

Physical and chemical properties of the soils

Soil form	Texture			Dominant clay mineral	CEC meq/ 100 g clay	Saturated Extract	
	% Clay	% Silt	% Sand			EC mS/m	ESP
Field simulation Longlands	18	12	70	Kaolinite/ Illite	43	53	2.0
Lab. simulation							
Longlands	13	11	76	Illite	41	64	3.5
Kroonstad	20	10	70	Illite/ Kaolinite	58	186	10.1
Rensburg	46	14	40	Montmorillonite	106	219	17.7

Discussion

Field rainfall simulation results showed that, where no cover existed, most soil was lost from the control treatment. In this treatment, final runoff rates were considerably higher and were reached much earlier, particularly in the second storm, indicating very low rainfall efficiency on an unprotected soil. The scattered tops left on the soil surface greatly reduced runoff by dissipating raindrop energy, decreasing crust formation and increasing time for water intake. As with trash, the effect of a surface cover also reduced the speed of water runoff, thus reducing its erosive energy.

Excess exchangeable sodium has a deflocculating effect on soil particles, reducing the stability of the soil, thus generating higher runoff and soil losses. Under rainfall simulation, it was noted that the IR was far greater and the FIR was reached much later when soil ESP was lower, although even a low soil ESP value resulted in a decrease in IR. This suggests that the sensitivity of these soils to marginal ESP values (2) is very high, and that their response is similar to that of soils studied in Israel (Shainberg *et al*[13]). Increases in ESP resulted in further decreases in FIR.

PG applied to the soil surface increases the concentration of electrolytes in the surface solution, thus reducing dispersivity of clay minerals and thereby minimizing crust formation and maintaining soil stability. In the field study, when PG was applied in combination with ST, runoff was reduced, crust formation decreased and the intake rate improved. The effect of PG in combination with ST was enhanced when the higher rate of PG (5 t/ha) was applied. Thus it is likely that the improved efficiency of PG in the presence of ST was due to the increased solution of the ameliorant by moisture retained in the tops, and the increased infiltration time.

The effect of ESP should not be considered independently of clay mineralogy and content. The texture of the Longlands/Kroonstad form soils, with moderate clay contents, makes them susceptible to crust formation. Sandier soils have a clay content which is too low to cause meaningful dispersion and pore blockage, while soils of higher clay content are more stable due to the binding action of the clay particles (Frenkel *et al*[4]; Levy and van der Watt.[7]). However, as clay content increased from 13% to 43% (Table 1) ESP values increased from 2 to 18. As higher rates of runoff occurred at the higher clay contents, it is thought that the dispersive effect of the higher ESP values overcame the cementing effect of the higher clay percentage. The clay assemblage of the Longlands/Kroonstad form topsoil was mainly illitic (65% vermiculite and chlorite) with secondary kaolinite and accessory amounts of smectite. The Rensburg form topsoil was composed of mainly montmorillonitic clay minerals, and displayed the lowest IR and FIR during the storm. Illitic soils are known to be more resistant to both mechanical and chemical deterioration and thus form less dense crusts and maintain higher FIR values. The mainly illitic topsoil of the Kroonstad form soil was, however, unstable and more susceptible to runoff losses and crust formation with an increase in sodic conditions. Even at low ESP values, the stability of these soils was affected, resulting in increased runoff and soil loss. The sensitivity of the 2:1 lattice clay to crust formation and chemical dispersion was far greater, as reflected by the lower FIR (Dewey *et al*[3]).

The PG treatments improved rainfall efficiency under both field and laboratory rainfall simulation by delaying the commencement of runoff, increasing the time for infiltration and reducing the rate of runoff. For the soil with low ESP, increasing rates of PG consistently decreased runoff volume. It is likely that the improved efficiency of phosphogypsum with an increase in ESP was due to the maintenance of clay flocculation, so improving soil hydraulic conductivity by the continuous release of electrolytes in solution. In the soil of moderate ESP, the effect of 2,5 t PG/ha did not result in a marked decrease in runoff. The low rate of PG in the presence of moderate soil ESP values appeared to be unable to overcome the dispersive effects of sodium, and resulted in no significant reduction in runoff losses. The effect of PG on soil loss appeared to be more marked with an increase in ESP. Although a 30% increase in clay content occurred across the site, the effect of increased aggregation was ne-

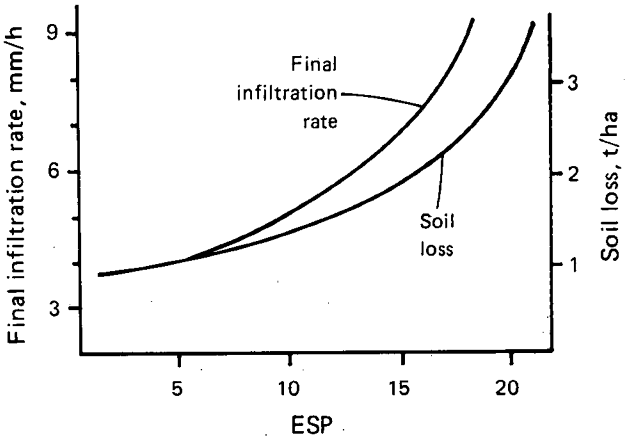

FIGURE 10 Relationship between ESP and FIR and soil loss when 5 t PG was applied/ha.

gated by increased dispersion caused by the higher ESP, as the effect of sodium is to weaken soil aggregation and stability.

For all treatments, soil loss was greater where ESP values were higher due to greater dispersion, higher runoff rates and thus higher erosive potentials. The response of IR and soil loss to 5 t PG/ha at varying soil ESP values is shown in Figure 10. The response to 5 t PG/ha at relatively low ESP values was negligible, but at higher ESP values there was a marked improvement in IR and soil loss was further reduced. From this type of response curve, it may be possible to determine threshold values for recommending rates of PG on different soil forms within the sugar industry.

Conclusions

Crust formation appears to be caused by two processes: physical breakdown under raindrop impact, where sodium is not part of the process; chemical dispersion dependent on the ESP of the soil and the electrolyte content of the applied rainfall. Although some soils had a high soil solution electrolyte concentration at the surface, the effect of high levels of sodium caused chemical deterioration at all ESP values above 2. However, the surface of the soil is sensitive to crust formation even at a low ESP value (1,5), due to raindrop impact as well as a low electrolyte concentration. The application of PG appeared to be more beneficial as ESP increased, counteracting the dispersive effects of excess sodium and preventing the sharp decline in IR. Phosphogypsum, in combination with scattered tops, delayed the commencement of runoff, reduced runoff rates and lowered the total amount of water lost. This combined treatment resulted in runoff values similar to those occurring beneath a trash blanket. The response to PG was dependent on soil ESP, electrolyte concentration and clay mineralogy; all of which should be taken into account when threshold values for recommending rates of PG on various agricultural soils are estimated. The beneficial effects of phosphogypsum are probably of most value to the unprotected soil during the first few months following planting or after harvesting a burnt ratoon crop.

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