AN ABSTRACT OF THE THESIS OF

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Title: The Effects of Gypsum on Infiltration and Surface Properties of Some Western Oregon Soils

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The effects of broadcast gypsum on infiltration rates, crusting, aggregate stability, and runoff and sediment yields were analyzed during the winter months on three West Oregon soils. The results were used to evaluate its utility as a management tool to help control erosion.

An application rate of two metric tons per hectare was used in the first season of testing. No differences were found between treated and untreated soil for infiltration rates, crust thickness and porosity, and aggregate stability. Runoff and sediment yields were too variable to discern differences between treated and untreated soil.

The range of application rates were increased to 4, 8, and 16 metric tons of gypsum per hectare in the second season of testing. These evaluations were made at one site. The highest rate was used for comparative purposes with the untreated soil. Infiltration rates were consistently lower while sediment yields and concentrations were higher from the treated soil throughout the season. Water stable aggregate size distribution was lower in the treated soil. It was postulated that crust strength was reduced by the gypsum application. The soil sur-

face aggregates from the treated soil were consistently higher in moisture content. This decreased the infiltration rates and provided a more erodible condition. Runoff and sediment yields from the erosion plots were more dependent on vegetative cover than on treatment.

The Effects of Gypsum on Infiltration
and Surface Properties of Some
Western Oregon Soils

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THE EFFECTS OF GYPSUM ON INFILTRATION AND SURFACE PROPERTIES OF SOME WESTERN OREGON SOILS

I. INTRODUCTION

1. Statement of the Problem

Soil erosion has plagued man since modern agriculture has existed. In the early years of America it was possible to ignore the problem due to the availability of virgin land. If a parcel of land became badly eroded the farmer often moved onto other land. Later, tenant farming and farm credit fueled the problem as the farmer viewed farming as a marginal business and looked for the short term low input profit. As erosion became more widespread and severe, people became concerned. The huge gullies and silt ladened air which developed the dust bowl made farmers recognize the vulnerability of their soil resource. These erosive events were primarily due to exhaustion of the soil by overcropping without replenishing the soil with nutrients and physical amendments. This left the soil bare of vegetation with resultant severe erosion, especially in the intense rainfall area of the midwest, the great plains, where unobstructed wind moved vast quantities of soil, and in the cotton land of the south.

National awareness led to action which was initiated in 1936 when grants-in-aid were first used for soil conservation under the Soil Conservation and Domestic Allotment Act. Technical assistance was available through the Soil Conservation Service, Civilian Conservation Corp., and the Tennessee Valley Authority. The main obstacle to conservation practices seemed to be agricultural instability, but as the government moved in directions to help stabilize this way of life, conservation practices grew.

In 1934 an erosion reconnaissance survey classified 40% of all land in the United States as moderately eroded, and 15% either as severe or destroyed for tillage (Soils and Men, USDA). Much of the problem was attributed to unsuitable land being cultivated. Presently it is estimated that four billion tons of soil are lost each year in the United States, with three billion tons from agricultural and forested lands (Beasley,1972). Loss of nitrogen, phosphorus, and potassium attached to the soil is estimated at more than 50 million tons (Taylor, 1966), worth over seven billion dollars (Beasley, 1972).

The removal of soil and nutrients cause many problems on the field and downstream. The loss of soil reduces production potential and quality of the crops. Deposition on fertile soil, loss of cropland, and division of fields are major concerns. Downstream, sediment reduces the capacity of channels and reservoirs resulting in flooding and reduced water supplies, reduces the value of streams for wildlife and recreation, and increases costs of maintaining navigable channels and harbors. Sediment is by far the greatest pollutant of water in terms of volume.

Although erosion control practices have been known since the early 1900's, implementation of these practices is a matter of public attitudes and policies. It was recognized that in order to control erosion one needed to protect the soil surface from raindrop impact, to absorb the water, and to move excess water off unerosively. Suggested erosion control practices included grassed waterways, good vegetative cover, contour plowing and planting, and terracing. These measures altered the factors which effect erosion; 1) soil erodibility, 2) slope length, 3) slope steepness, 4) vegetative cover, 5) rainfall, and 6) management practices. These factors were analyzed and evaluated for their significance in contributing to soil erosion and an equation predicting soil loss was derived by Wischmeier and Smith (1965).

Although erosion control measures have been known for 80 years, erosion is still a serious problem. Lack of action is due in part to economics which was discussed earlier, but also to the unique nonpoint source nature of most eroded material. Therefore, public awareness demanded federal regulation. The first of these were the Water Quality Act of 1965 and the Water Pollution Control Act of 1966. The latest regulation is Public Law 92-500 which states that nonpoint source pollution, and therefore agricultural pollution, must be controlled within set guidelines.

Erosion is a hazard on the sloping agricultural lands in Western Oregon, especially for fall planted crops such as wheat. The growth of wheat in the fall is very limited before onset of the winter rainfall season. This leaves the soil with a minimal protective cover; a cover that can be important in preventing erosion by reducing raindrop impact and runoff velocity. It is during the winter months of October through March that W. Oregon receives nearly 90% of its 100 cm yearly total of rainfall. Unfortunately, many of the conventional erosion control measures are not applicable to this region. Contour plowing and planting are not practical as the fields are small and highly dissected. For the same reason terracing is not used in the region.

Management practices for the most part are measures used to decrease the contribution of the factors that effect erosion. One management practice which may be applicable is decreasing the erodibility of the soil through the use of amendments. Soil aggregation and aggregate stability have been shown to be highly significant in determining soil erodibility (Wischmeier and Mannering, 1969; El-Swaify and Dangler, 1976). Maintaining aggregate stability would keep infiltration rates high by maintaining a porous soil surface. The formation of a crust is mostly due to the breaking down of soil aggregates with the fine particles filling the pores (McIntyre, 1958b). The crust reduces infiltration, resulting in increased runoff (Edwards and Larson, 1969; Hillel and Gardner, 1969; Duley, 1939). Duley stated that this phenomenom is the most important factor affecting infiltration on the soils he studied. Even if nearly saturated conditions exist and infiltration is controlled by the water content of the soil, more stable aggregates are less likely to be transported by overland flow. The more stable aggregates would not breakdown and would need higher energy conditions to be transported than dispersed individual soil grains.

Several artificial amendments to maintain aggregate stability and reduce crusting have been studied with positive results (Allison and Moore, 1956; Cruse and Larson, 1977; Bennett et. al., 1964). Generally, these chemicals are too expensive for agricultural use on a large scale. A source of polyvalent cations may also reduce aggregate destruction by their replacement of monovalent cations. Gypsum and lime are two amendments which are economically feasible. Reducing the effective surface charge density of soils can increase aggregation. The effective surface charge density of soils varies not only with pH, but also with electrolyte concentration. In addition, where cations such as calcium are adsorbed, the effective charge density is less than with monovalent ions. Swelling and particle dispersion are reduced and problems with crusting are decreased. Gypsum should be more effective than lime since it is a source of calcium ions but doesn't raise the pH and consequently, the surface charge density is not raised (Uehara and Jones, 1974). The use of gypsum is well documented for the reclamation of sodic soils. Its effect on acid soils has not been evaluated to any significant degree. It was hypothesized that the addition of gypsum to the soil surface would maintain aggregate stability. This would reduce the formation of a crust and result in higher infiltration rates than untreated soil.

2. Objectives of the Study

1) To determine the effect of gypsum on some of the physical properties of acid soils.
2) To determine if the resulting changes in soil properties influence runoff and erosion.

It was intended that if the results of the study were favorable, they would form a basis for recommending gypsum as a management tool for erosion control.

II. GENERAL METHODS

1. Location and Description of the Watershed

The watershed used in the study is located in Polk County, Oregon, 3.2 km southwest of the town of Monmouth (Fig. 1). It is 285 hectares in size, and is situated in R.5W. and T.9S. This area is in the high winter rainfall zone of Western Oregon where, on the average, 90% of the yearly rainfall of 100 cm occurs from October through March. The three sites chosen for this study were located in different subwatersheds within the watershed. Most of the watershed was planted in winter wheat. Planting generally occurs in early October resulting in a very low crop cover for the majority of the rain season. Some of the lower portions of the watershed were planted to perennial grass. The main drainageway of the upland portions used for winter wheat was also planted with grass. The watershed consists of rolling, highly dissected hills with a variety of slopes and aspects. Because of this, the operators do not practice contour plowing or planting. The mean elevation of the watershed is approximately 90 m, ranging from 66 to 150 m above sea level. The drainage of the watershed eventually empties into the Luckiamute River. This site was chosen for an erosion research project because of the variety of soils, the possibility of excessive erosion due to planting winter wheat on sloping lands, and the cooperation from the farmers involved. For a more detailed description of the watershed and the soil-geomorphic relationships, refer to Glasmann (1979).

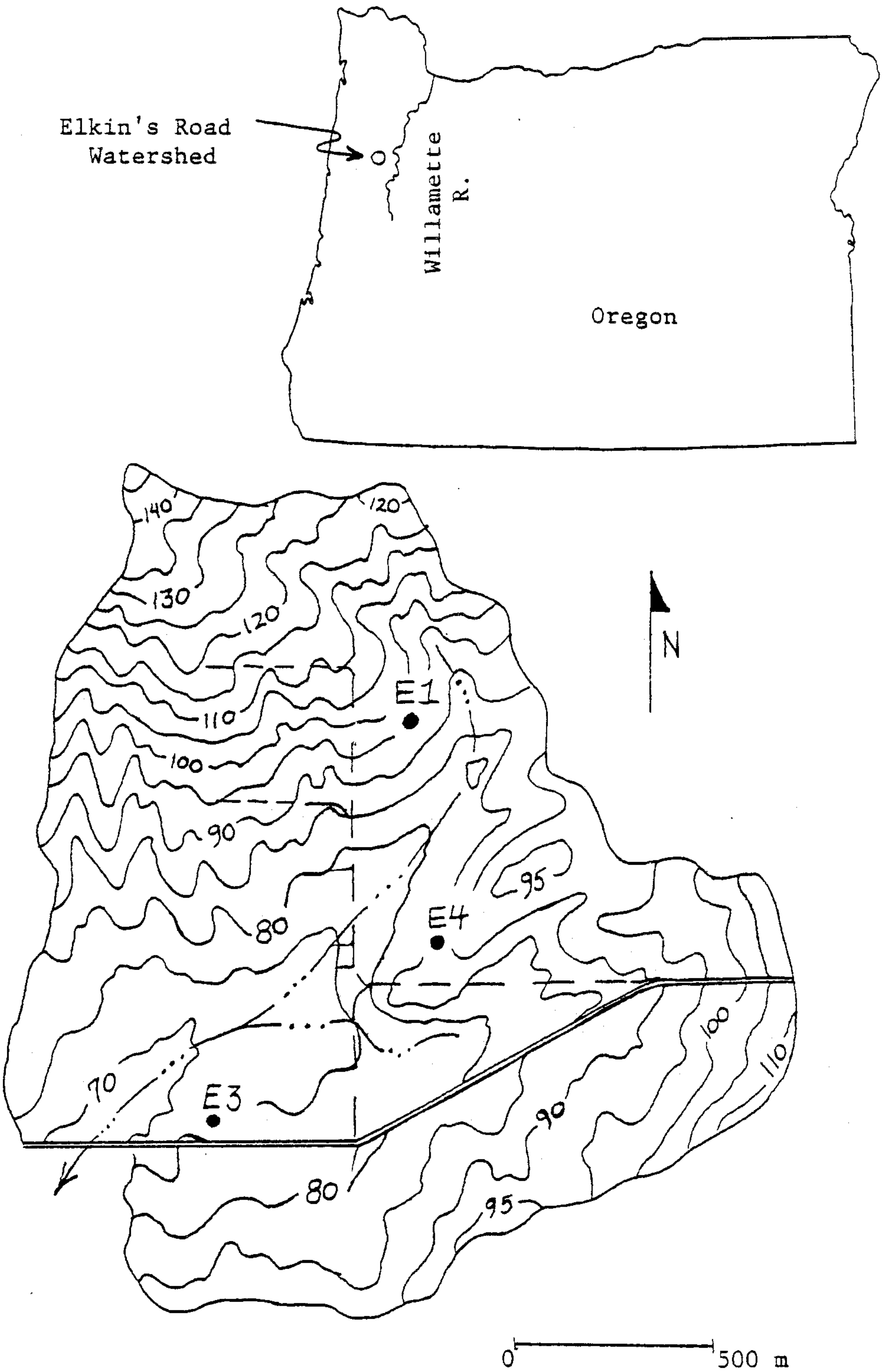


Figure 1. Location and contour maps of the watershed with study sites located. Elevations are in meters.

A broadcast treatment of gypsum was applied at the rate of zero and two metric tons per hectare the first season, and 0, 4, 8, and 16 metric tons per hectare the second season. The increase in application was in response to the fact that no effects were observed during the first season. These applications were to the erosion plots for measurement of runoff and erosion. An adjacent area also received the highest rate of application; the adjacent area was used for testing infiltration and sampling for crusting and aggregate stability. This allowed the runoff plots to be undisturbed during the rain season. A reapplication of 16 metric tons per hectare was made to the adjacent area and to the highest rate plot on Febuary 24 of the second rainfall season. The gypsum used was of the quality commonly used by farmers and contained 65% $CaSO_4 \cdot 2H_2O$.

2. Nature of the Soils Studied

Three different sites within the watershed were studied (Fig.1). One site, designated E3, was located in the perennial grass field portion of the watershed. This site occupies an area with a slope of 5%, and a westerly aspect. It is located on Woodburn silt loam, which is classified as a fine-silty, mixed mesic Aquultic Argixeroll. This site is moderately well drained. Two study sites were located in the portion of the watershed which was planted to winter wheat. One of the sites, designated E1, is a well drained site located on a 7% slope with a southern aspect. The soil is mapped as a Willakenzie silt loam, a fine-silty, mixed mesic Ultic Haploxeralf. The other site, designated E4, is also mapped as a Willakenzie silt loam, but is underlain by a slowly permeable layer located 46 cm below the surface. This restrictive layer causes a perched water table to develop during the winter months. This site is somewhat poorly drained. It has a slope of 7% with a western aspect.

Organic matter content and particle size distribution of the top two cm of each soil were determined. For a complete profile description of the three soils studied refer to the appendix. The descriptions were taken adjacent to the erosion plot sites.

Table I. Physical characteristics of surface soil† at various sites.

Site	Sand	Silt	Clay	Organic matter
	%			
E1	31.7	48.0	20.3	2.27
E3	4.5	70.0	25.5	3.85
E4	10.8	62.0	27.2	3.46

†Upper two cm of soil.

Table II. Chemical characteristics of surface soil† at various sites.

Site	pH		Extractable bases				CEC	Base saturation
	H_2O	.01M $CaCl_2$	K	Mg	Ca	Na		
			meq/100 g					%
E1	6.2	5.6	.21	.42	4.9	.23	8.47	65.6
E3	5.5	5.3	.46	2.2	6.6	.11	18.02	52.0
E4	5.3	4.8	.37	1.5	5.2	.12	13.30	56.7

†Upper two cm of soil. (Extractable bases, CEC, and base saturation analyses performed by Soil Testing Laboratory, O.S.U.)

III. INFILTRATION

1. Review of Literature

Infiltration is the term applied to the process of water entry into the soil, generally through the soil surface and vertically downward (Hillel, 1971)

The process is of practical importance since its rate influences the amount of runoff generated. There are three factors which affect the infiltration rate. These are 1) the cross sectional area and character of the channels through which the flow takes place, 2) the energy gradient under which flow takes place, and 3) the viscosity of the fluid (Lewis and Powers, 1938). Gypsum may affect infiltration by reducing the destruction of the soil aggregates, thereby maintaining the porosity of the soil surface. Reducing crust formation will also retain the rough nature of the soil surface which can detain runoff water until it infiltrates.

The character of the channels, or porosity and pore size distribution, is influenced by tillage, organic matter, structure, texture, macropores from root channels and animal burrows, shrinkage cracks, moisture content, swelling of colloids, inwash of silt, entrapped air, and plant residue.

Tillage can increase the infiltration rate by providing a more porous top soil (Musgrave and Free, 1936). However, a tilled field may experience a rapid reduction of infiltration due to the structural disturbance of the surface making it more susceptible to the beating action of rainfall and subsequent formation of a crust. Duley (1939) showed a crust had more of an affect on infiltration than moisture content or other profile characteristics. The formation of a crust reduces the porosity at the soil surface due to the breakdown of soil aggregates into soil grains which plug the pores. A large part of this is from the inwash of silt (Horton, 1935).

Organic matter (differentiated from plant residue here) has been shown by McCalla (1942) to increase infiltration in loessial subsoil by increasing the water stability of soil structure. Johnson (1957) noted that the products of decomposition caused a clogging of soil pores and resultant decreased infiltration rate. However, initial rates were high upon incorporation of organic matter and Johnson felt this was of more importance. The incorporation of plant residue has been shown to increase infiltration rates by providing macropores and protecting the soil surface from rainfall, thus maintaining its open surface (Lowdermilk, 1930).

The swelling of colloids in the soil reduces the porosity and hence the infiltration. Browning (1939) observed this phenomena to be greater in the surface soil than the subsoil even though the surface soil was lower in clay. He attributed the lesser expansion in the subsoil to its compact nature providing less space for expansion.

Entrapped air also reduces infiltration by reducing the pore space through which water can flow. Christiansen (1944), Zimmerman (1936), Free and Palmer (1940), Garner et. al. (1969), and Wilson and Luthin (1963) describe the complex interrelationship which exists between entrapped air and an advancing wetting front.

The soil water also influences infiltration by occupying pore space and thus reducing infiltration. Lewis (1937) and Tisdall (1951) both report that antecedent moisture is a major factor in determining initial infiltration rates. But, the longer the time of precipitation the less effect antecedent moisture would have on infiltration rates.

Of importance besides the total porosity of the soil is the distribution of pore sizes. Amount of flow increases with the fourth power of the cylindrical tube diameter according to Poiseuille's equation. A few macropores have the ability to contribute greatly to infiltration (Dixon and Peterson, 1971). Animal burrows, root channels (Horton, 1935), earthworm channels (Hopp and Slater, 1948), and shrinkage cracks (Matthews, 1916) all provide macropores to the soil. The difficulty in collecting data which reflects the contribution of large pores is one reason for the little attention given this subject in the past. For the pores to contribute to infiltration they must be open to free water at the surface. Otherwise, large pores are not utilized until the surrounding soil is saturated. The channel system described by Dixon and Peterson is a means by which free water is distributed into the soil matrix and air vented to the surface.

Another general factor which governs infiltration is the viscosity of the water. The viscosity of the water is dependant on the water temperature which is influenced by air and soil temperatures. The greater the temperature the less viscous the water. Higher water temperatures should correspond to a greater infiltration rate as the water can move more freely. Moore (1941) found this to be true between temperatures of 5°C and 35°C.

The pressure gradient also governs infiltration and is effected by the moisture content and the distance of the wetting front. In a dry soil the pressure gradient is high initially and infiltration is high due primarily to matric forces. With time the distance of the wetting front increases and the movement of water is controlled by gravitational forces. The matric force is decreased because of the increased distance to obtain the same potential difference that was present at the onset. The higher the moisture content the less the matric potential will contribute to water distribution and infiltration (Hillel, 1971).

Of all the factors listed as affecting infiltration, none of the authors stated there is a single factor which controls infiltration.

The measurement of infiltration has been done with the use of rainfall simulators. Several types exist and they can be categorized as spraying simulators or non-pressurized droppers.

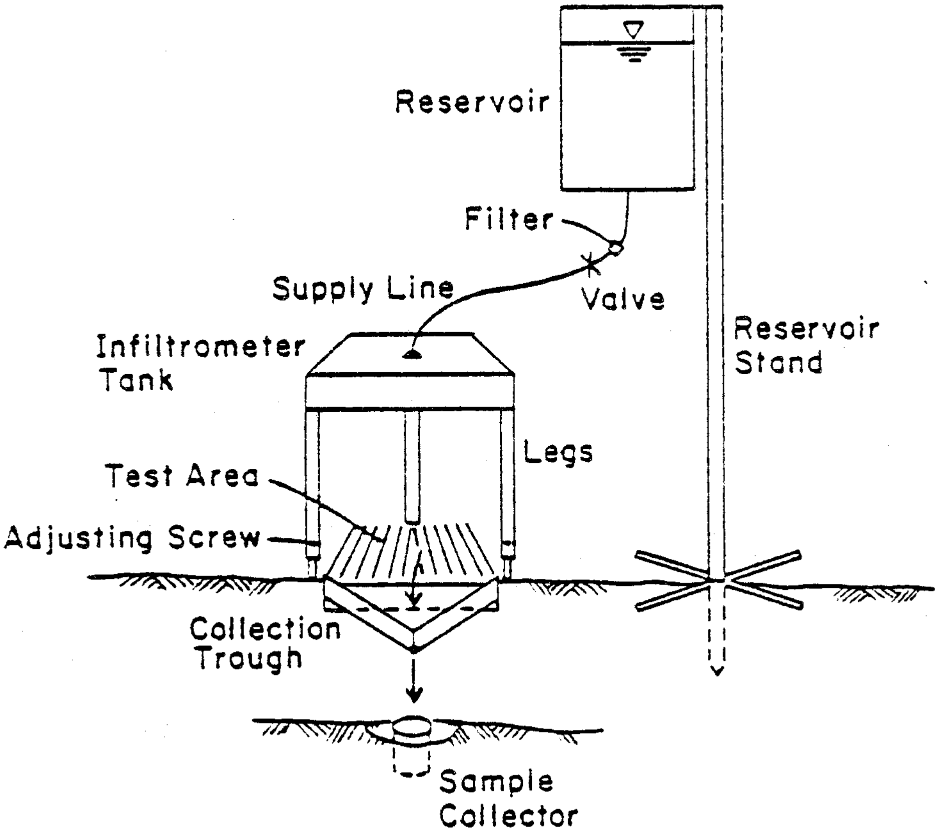
Spraying simulators use nozzles with water under pressure. The first design to reproduce drop size distribution and intensity of natural rainfall was the Type F nozzle (Wilm, 1943). The nozzle sprayed water upwards, but the drops didn't attain terminal velocity before striking the soil surface. This type of simulator only produced about one half the energy of natural rainfall (Meyer,1965). Around 1955, the importance of kinetic energy of falling raindrops in relation to soil detachment was recognized. This gave rise to simulators with downward sprays so the drops could attain terminal velocity before striking the soil surface. Meyer and McCune (1958), Swanson (1965), and Morin et. al. (1967) all developed spraying rainfall simulators to attain terminal velocity of the drops. The problem with these is that if the drops are to represent natural rainfall size distribution, large nozzles must be used. This produces a greater intensity than natural rainfall. The aforementioned investigators corrected this in different ways; 1) by spraying intermittently, 2) by rotating or moving the spray boom, or 3) by spraying continuously and shielding the soil intermittently.

Non-pressurized droppers were first developed in the 1940's and were intended for laboratory use. Larger units have since been used for field investigations. The first models used the drip method where drops were formed by cheesecloth and yarn over chickenwire (Ellison, 1947; Ellison and Pomerane, 1944; Osborn, 1953; Barnes and Costel, 1957). Adams et. al. (1957) used glass capillary tubes protruding through the base of a water supply tank and Meeuwig (1971) used hypodermic needles in his model. The disadvantage of the drip infiltrometers is that the drops do not attain terminal velocity before striking the soil surface. This problem is overcome with the use of "towers" which raise the water source high enough so the drops can attain 90-95% of terminal velocity (Parr and Bertrand, 1960). The towers have flared canvas walls to eliminate wind. Meeuwig's infiltrometer rests 50 cm above the ground. Mutchler and Hermsmeier (1965) state units such as these are adequate in low intensity rainfall zones.

2. Methods and Materials

Field infiltration tests were conducted using a portable, closed top infiltrometer modeled after an instrument described by Meeuwig (1971). The infiltrometer was constructed in the Soil Science Dept., Oregon State University, and differs slightly from the one constructed in the Forest Engineering Dept., Oregon State University, and described by Froehlich and Hess (1976). The infiltrometer consists of a plastic tank 61 cm square and 2.54 cm deep which rests on three legs (Fig. 2). The two in front are adjustable and the third leg in the middle of the back is stationary. This provides for proper leveling of the instrument which minimizes differences in drop intensity from the various parts of the infiltrometer. Precipitation is produced by 517 evenly spaced 23 gage stainless steel tubes through the bottom of the tank. An average drop size of 2.87 mm in diameter is produced. The unit sits approximately 50 cm above the ground. A 30 cm long manometer tube is screwed into one corner of the top of the tank. This allows the tank to fill rapidly as well as measure the pressure head produced by the water source. By measuring the pressure head, an application rate of water can be determined. The instrument was calibrated by collecting "rainfall" over a known period of time at a given pressure head. This was done for several different pressure heads.

The water source for the applicator is a five gallon water reservoir. A rubber tube is connected to the bottom of the reservoir and to a plastic standpipe screwed into the center of the top of the applicator tank. The rubber tube is approximately five m long. This allows the water source to be moved upslope and rested atop a metal T-bar to develop a pressure head. Along the tube is a gas filter to trap impurities and prevent plugging of the needles, and a screw valve to regulate flow. The plastic reservoir is open to the atmosphere to help maintain a constant head.



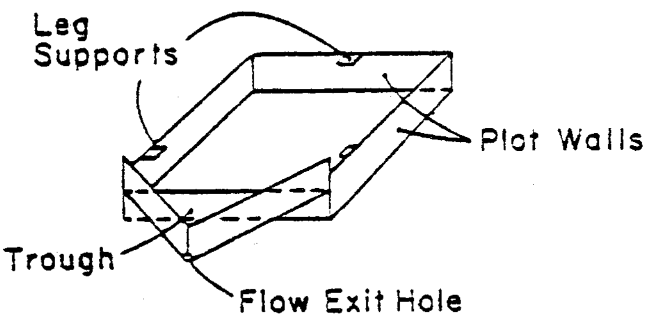


Figure 2. Portable infiltrometer (upper) and modified trough apparatus (lower).

The infiltrometer rests on a metal frame 66 cm square and nine cm deep which sets into the ground. The downslope side is open for runoff to be funneled by a trough into a collection bottle. The frame helped keep runoff water from running out of the plot area. Otherwise this water would be runoff but not recorded as such. The collection trough was positioned level with the soil surface when the frame was inserted into the ground.

Infiltration tests were conducted several times during the winter rain season when changes in the soil surface were observed or an appreciable amount of precipitation had fallen. The tests were made on similiar landscape position, and consideration was taken to select sites with similiar microrelief and orientation of rills. Subsequent infiltration tests were run on different sites than the ones used previously to avoid the disturbance created by the previous tests. Precipitation was applied at the rate of 7.2 cm/hr. This was necessary to provide measurable runoff and to maintain a constant head.

The amount of time for runoff to occur and to collect a measurable amount of runoff was noted for each sample. Several samples were collected during each infiltration test. Volumes were measured with a graduated cylinder and the samples transported to the lab for sediment concentration analysis. Infiltration rates were calculated and plotted against time. Surface soil samples were taken prior to the test to determine the gravimetric water content. Because of the size and nature of the infiltrometer, the infiltration values obtained are only relative and were used for comparing differences between treatments and time of year.

3. Results and Discussion

Differences between gypsum treated and untreated soil during the first season show no consistent trends due to treatment (Fig. 3,4,5). A general trend of a reduction in the time it takes to initiate runoff and a decrease in steady state infiltration (the portion of the curve where the infiltration rate is nearly constant) was evident as the season progressed into midwinter. The curves follow the general pattern described by several investigators. During a single infiltration trial, an initially high infiltration rate decreased with time. The decrease was primarily a result of a reduction in the matric potential from an increase in the moisture content of the soil (Hillel, 1971). Over the season the decrease in the time it took for runoff to occur was due to the formation of a crust. At site E4 (Fig. 3) before the formation of a crust, it took 12-14 minutes to initiate runoff. The porous surface from the recently plowed soil allowed the entry of water into the soil despite the high moisture content. Later in the year at the same site, the time for runoff to occur was reduced to less than one minute. This was a result of the crust which had formed. The crust saturated quickly and subsequent additions of water resulted in runoff. Further development of a crust reduced the steady state infiltration even more as seen on the trial date of Mar. 30.

At site E1 (Fig. 4) a general trend of an increase in steady state infiltration versus time of year was observed for the three trial dates. A low infiltration value on Feb. 25 was due to the high initial

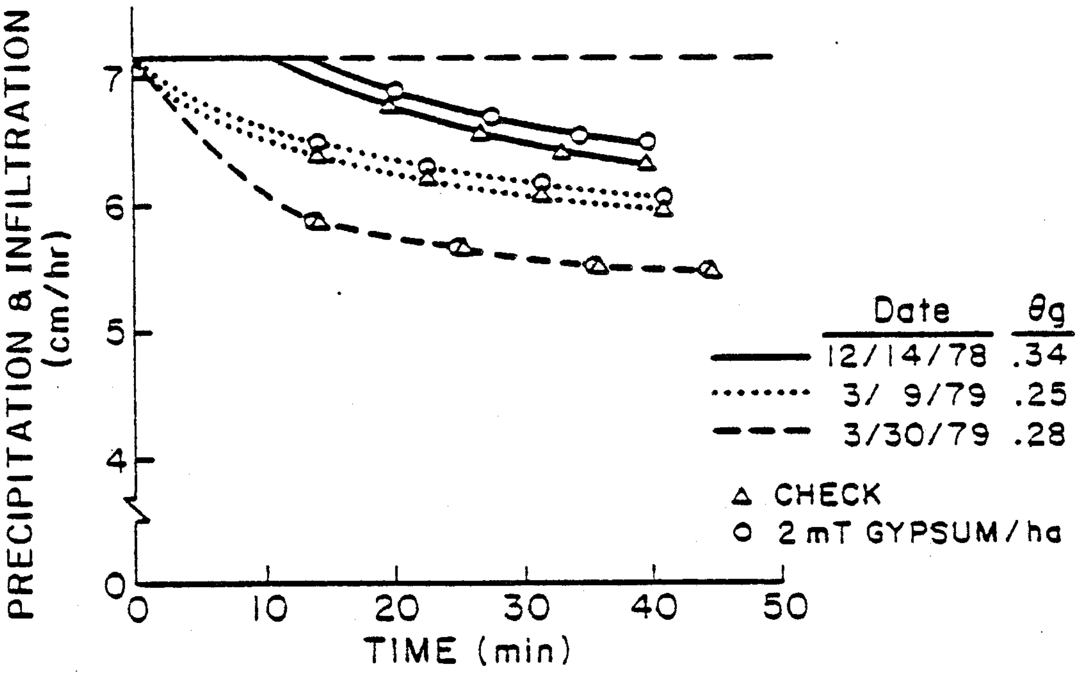


Figure 3. Infiltration rates at site E4, 1978-1979.

moisture content of the soil coupled with the crust which had formed. An increase in steady state infiltration on Mar. 12 was due primarily to a decrease in the initial moisture content of the soil and some minor cracking of the soil surface crust. On Apr. 6, the steady state infiltration was at a high value. This was due to extensive cracking of the soil surface crust which allowed water to enter the soil quite rapidly. The cracks were in a polygonal array with the largest ones being seven to eight mm wide and reaching several cm down into the soil. The cracking was due to drying of the soil and contraction of the soil clays. The increase in steady state infiltration from Mar. 12 to Apr. 6 was attributed mainly to cracking since the initial moisture content values were the same. The time to initiate runoff was still less than one minute. This was because a crust was still

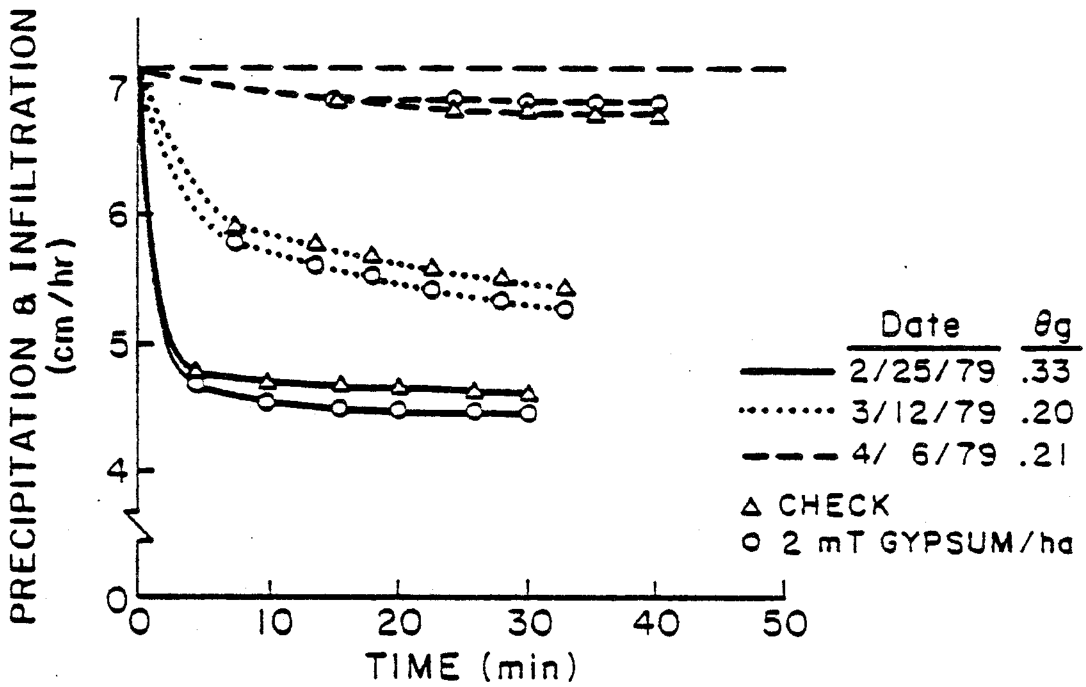


Figure 4. Infiltration rates at site E1, 1978-1979.

present which saturated quickly and produced runoff. The cracking was not observed at the other two sites until later in April and June for sites E4 and E3 respectively. The delay was a result of wetter conditions at these two sites. Site E4 has an impervious layer located in the subsoil which restricts drainage. Site E3 was located lower in the landscape and retained a high moisture content.

The infiltration curves for site E3 are given in Fig. 5. Early in the year the surface was relatively porous and moisture content low. This resulted in five to six minutes before runoff occurred and a relatively high steady state infiltration. Later in the rain season, the clogging of surface pores and high moisture content resulted in a short period of time to initiate runoff, and low steady state infiltration.

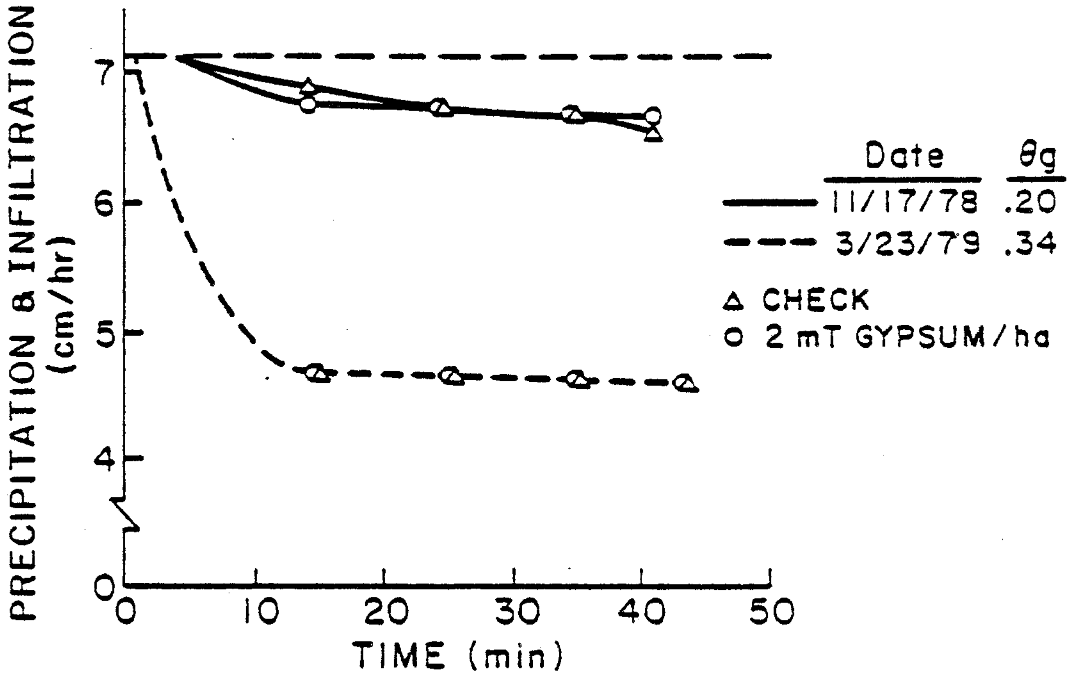


Figure 5. Infiltration rates at site E3, 1978-1979.

An effect of gypsum was observed for the second season of study at site E4 (Fig. 6) when higher rates of gypsum were applied. In five of the six trials the untreated soil had higher infiltration values. The time to initiate runoff was essentially equal between treatments and dates. The infiltration values decreased with time due to the factors mentioned previously. The higher infiltration values for the untreated soil was related to moisture content. On the seven dates that aggregate samples were taken, the gypsum treated soil had an appreciably higher moisture content on four of the dates while the other three dates showed no difference (Table III). The moisture content values listed on the infiltration curves are from the untreated soil.

The values obtained for the second rain season differ in some

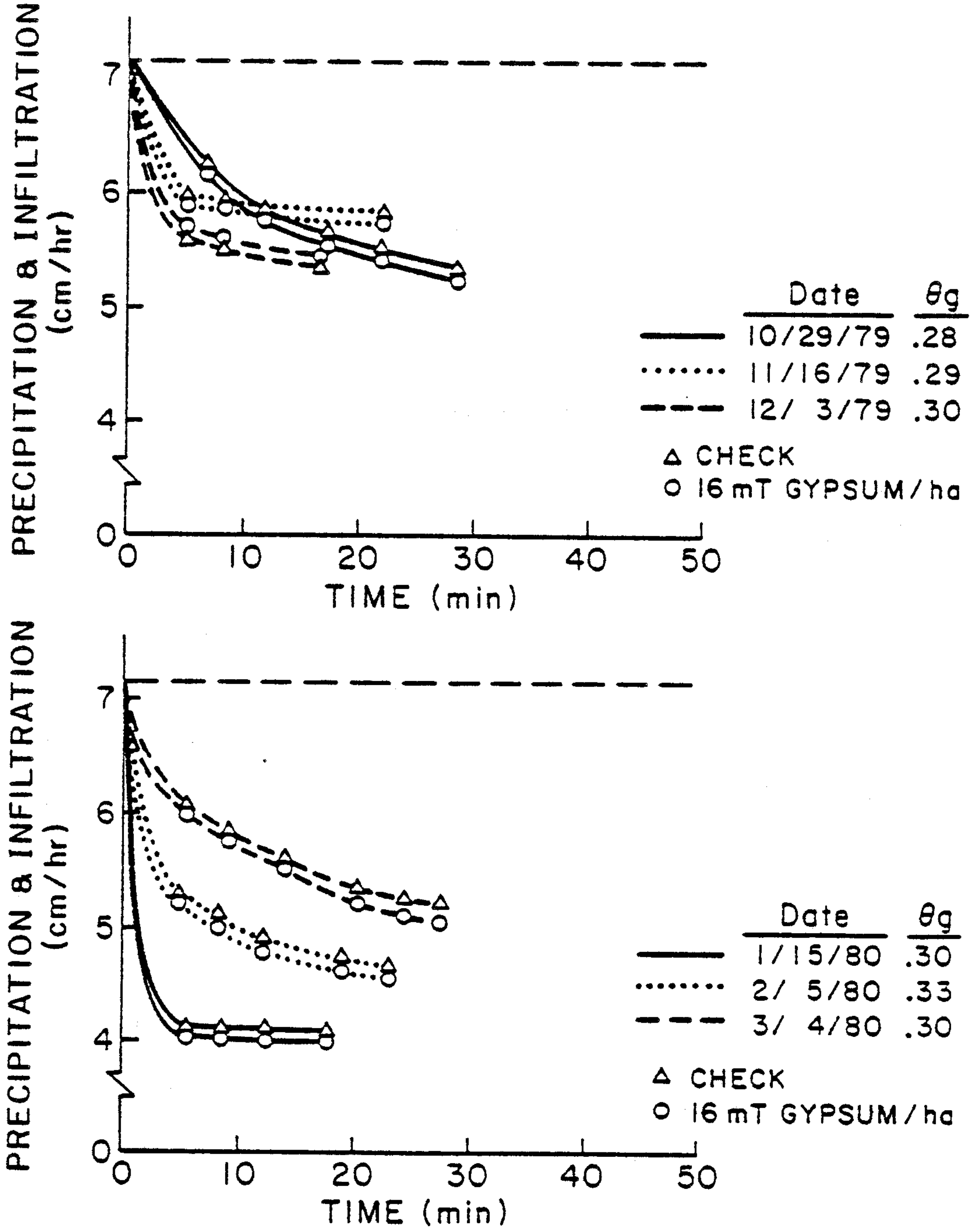


Figure 6. Infiltration rates at site E4, 1979-1980.

Table III. Moisture content of surface aggregates at site E4, 1979-1980.

Date	Gravimetric moisture content	
	Treated†	Check
Oct. 23	0.248	0.248
Nov. 6	0.280	0.280
Nov. 16	0.308	0.267
Dec. 3	0.320	0.283
Jan. 3	0.280	0.285
Feb. 5	0.333	0.319
Mar. 4	0.331	0.278

†16 metric tons of gypsum per hectare.

respects from those obtained the first season. There was no time delay for runoff to occur at the beginning of the season. This was due to the formation of a rill crust from a rainstorm in late October. Subsequent trial dates show a slight decrease in steady state infiltration with a low value observed on Jan. 15. The moisture content for these first four trial dates were essentially equal, so the differences are attributed to crusting of the soil surface. On Feb. 5 and Mar. 4 increases in steady state infiltration were observed. No cracking was observed at this time. The moisture contents were the same as earlier dates. The increase in infiltration is postulated to be the result of an increase in crop cover.

In much of the discussion dealing with infiltration, there was no implication to absolute values which duplicate natural rainfall. The values obtained are believed to be much higher than those that actually exist. There are several reasons for this. First, the infiltrometer covers a small area, therefore the possibility for lateral movement of water and air was increased. This would not occur in a rainstorm where rainfall is distributed over the entire soil surface. This would also increase the effects of trapped air and thus reduce infiltration. Finally, the effects of the long duration precipitation periods was lacking. The infiltrometer was set up after a rainstorm or during an interstorm period. Movement of water out of the soil had already taken place lowering the water table. It is believed that surface runoff does occur under unsaturated conditions in midslope positions. The concept of partial area contribution to runoff must be taken into account even at midslope positions. Rill areas were seen early in the season contributing to runoff even though the profile was unsaturated. Although the infiltrometer lacks in obtaining true absolute values, results are valid for determining relative differences and for identifying the factors and processes involved.

IV. AGGREGATE STABILITY AND SIZE

1. Review of Literature

Some mention has already been made about the importance of aggregate stability on maintaining infiltration rates and decreasing soil erodibility. Soils made up of stable aggregates (ones that resist degradation from the action of water) will maintain a porous surface for infiltration of rainfall. As unstable aggregates breakdown from the impact of rainfall, a crust which is very low in porosity can form. This can reduce infiltration as has been pointed out earlier. There will be more runoff and erosion as a result. The dispersed soil particles are much more easily transported with overland flow than the larger stable aggregates. Woodruff (1939) related the penetration of water to aggregate stability. Middleton (1930) and Middleton et. al. (1934) related the degree of aggregation to the erodibility of the soil. Emerson (1959) and Greenland (1965a&b) state that one of the most important factors governing soil loss by water is structural stability. Adams et. al. (1958) stated that the soil properties that effect erosion are those that 1)effect infiltration, and 2)resist dispersion. Certainly aggregate stability affects both of these properties.

The size distribution of stable aggregates also has an important effect on the intake rate of surface soils. Large soil fragments will help maintain a high intake rate (Larson, 1964; Burwell et. al., 1966) and will contribute to surface roughness. A rough surface will help detain runoff, providing more time for infiltration, and it will reduce the velocity of runoff.

The mechanisms of aggregation are not fully understood, but many mineral and biological components have been recognized as contributing to aggregation and aggregate stability. The general procedure in evaluating these constituents is to measure the aggregate stability before and after one of the constituents has been removed. The resultant difference in aggregate stability can be attributed to the constituent. Evaluation of organic substances, iron, aluminum, and microbial products has been done in this manner. This same concept can be used in evaluating the effects of a soil amendment. Such amendments as synthetic polymers, mulches, plant residue, and agri-chemicals (lime, gypsum,...) have been evaluated on this basis.

Developing a suitable means by which to measure aggregate stability has always been a problem. Laboratory analysis in most cases involves a disturbance of the soil in sampling. Moreover, most of the laboratory analyses involve more rigorous conditions than those encountered in the field. Therefore, it it almost impossible to make generalizations about what has been determined in the lab and relate it to what is happening in the field. Comparisons between aggregates treated differently can be made, however, on a relative basis.

Most measurements of aggregate stability involve the resistance of an aggregate to slake or breakdown due to an external force. This force is usually falling water drops or sieving in water, although various water, alcohol, ether, acetone (Dutt, 1948), and glyceol (Davidson and Evans, 1960) mixtures have been used. The amount of dispersion is measured by the use of a turbidimeter (Davidson and Evans, 1960), the reduction of water or air permeability (Reeve, 1953), or by the reduction in aggregate size and amount recovered by the use of sieves. The use of sieves has been the most popular and involves two general methods. One is the water sieve method where soil aggregates are sieved in water for a period of time in a single size or nest of sieves. This was first described by Yoder (1936) and has been used by many investigators with slight variations to determine both aggregate stability and stable aggregate size distribution (Russell and Feng, 1947; Garey, 1954; Bryant et. al., 1948; Miller and Kemper, 1962). The other method involves subjecting a soil aggregate to falling water drops and counting the number of drops it takes to breakdown an aggregate of known weight. This was developed in response to the recognition of rainfall as an important agent in initiating soil erosion. McCalla (1944), Vilenskey (1945), and Bruce-Okine (1975) have all used this method in determining aggregate stability. Many slight variations exist for each method. This is because investigators have recognized the variability that initial moisture content, storage method and time, method of prewetting, size of aggregates used, duration of test, and other factors have on the results attained.

There are several ways to express the data obtained from the determination of stable aggregate size distribution. Geometric mean diameter (GMD) (Mazurak, 1950), mean weight diameter (MWD) (VanBavel, 1950; Youker and McGuinness, 1956), weighted mean diameter, and standard deviation (Puri and Puri, 1939), coefficient of aggregation (Retzer and Russell, 1941), and aggregate size distribution curves have all been used in expressing aggregation data. Schaller and Stockinger (1953) compared five methods for expressing aggregation data and reported that the best methods seemed to be the MWD or GMD and the log standard deviation. The correlation coefficient between the MWD and GMD was 0.9. Both of these indices can be used to represent aggregate size distribution for statistical purposes.

2. Methods and Materials

Samples were taken on several dates during the winter rainfall season from treated and untreated soil. Samples were taken when the soil surface was somewhat dry so that the aggregates would not slake during sampling. After a crust had formed, samples were taken by removing the upper two cm of soil with a knife. Samples were stored in a plastic container in a cooler until the analyses were conducted. Maximum storage time was one week.

Soil surface aggregates were measured for stability using the water drop method described by McCalla (1944). A soil aggregate weighing between 0.10-0.20 grams dry weight equivalent was placed on a sieve with a one mm mesh. Air dried soil was used for the first season analyses, and both air dried and moist soil for the second season analyses. Drops of distilled water four mm in diameter released from a burette fell 30 cm before striking the soil aggregate. Drops were applied at an intensity of one drop per two to three seconds. Drops were counted until the soil aggregate was broken down to the point of being washed through the screen. Tests involving the moist soil aggregates produced two endpoints. Aggregates collected early in the season would breakdown into several small aggregates which resisted further degradation. These results are reported as the number of drops per 0.10 gram of soil after which further slaking is miniscule. Moist aggregates sampled later in the season as well as all air dried aggregates broke down completely. These results are reported as the number of drops to destroy 0.10 gram of soil. Forty individual determinations for the air dried aggregates and 25 individual determinations for the moist aggregates were made for each sample date.

A variation of the water sieve method, first described by Yoder (1936), was used to determine stable aggregate size distribution. Soil retained at its moisture content when sampled was used. The equivalent of approximately 60 grams dry weight of soil was placed in the top sieve of a nest of five 20 cm brass sieves. The sieve openings were 8.0, 4.7, 2.0, 1.0, and 0.5 mm. The sieves with the soil were immersed in water for ten seconds, and then oscillated in water for five minutes at the rate of 29 strokes per minute with a displacement of 37 mm using a Yoder type machine. The sieves were removed from the water and the water stable aggregates washed into an evaporating dish and dried at 110°C. The dry weight for each aggregate size was measured and used in calculating stable aggregate size distribution, percent of aggregates recovered, mean weight diameter, and geometric mean diameter.

3. Results and Discussion

Aggregate stability was measured using air dried aggregates the first winter rain season. Differences were found between treated and untreated soil for two sample dates at each site (Table IV). However, the direction of differences are not consistent and the magnitude is small.

Whereas differences between treated and untreated soil are small or negligible, differences between sites and dates of sampling are quite evident. At all three sites the greatest decrease in aggregate stability occurred between the first two sample dates. The decrease in aggregate stability in the early part of the season was postulated to be due to raindrop impact. The soil was in a porous, aggregated, dry condition at the beginning of the season. The first rains penetrated the dry aggregates and reduced the cementing between particles. This process broke down the aggregates through the mechanism of entrapped air. At the end of the season there was a slight increase in aggregate stability. The increase was postulated to be due to either an increase in microbial activity or wetting-drying cycles.

The differences between sites was strong with E3>E4>E1 in terms of initial and overall aggregate stability. This correlates with organic matter content with E3(3.85%)>E4(3.46%)>E1(2.27%). Although much literature exists on the importance of organic matter in aggregate stability, these are only three data points and many more would be needed to derive a statistical relationship.

During the second rain season the values for aggregate stability were similar to the first season (Table V). Site E4 initially had a high value, but this decreased to a low value by Nov. 16 after which

Table IV. Aggregate stability at various sites as determined by the water drop method using air dried soil, 1978-1979.

Date	Drops to destroy 0.10 gram of soil					
	E1		E3		E4	
	Treated†	Check	Treated	Check	Treated	Check
Nov. 15		28.40		55.40		47.00
Dec. 22	9.60	8.40			14.13	15.20
Jan. 21	10.15	10.18	13.75	16.33*	14.23	15.05*
Feb. 8	10.88	10.63	16.15	16.80	14.90*	14.18
Mar. 9	10.70	12.90*	15.15	16.08	14.53	15.05
May 4	16.13*	14.43	25.30*	19.80	14.45	14.20

†Two metric tons of gypsum per hectare.
*Significant difference between treatments at the 0.05 level.

Table V. Aggregate stability at various sites as determined by the water drop method using air dried soil, 1979-1980.

	Drops to destroy 0.10 gram of soil			
	E1		E4	
Date	Treated†	Check	Treated	Check
Oct. 23				24.56
Nov. 6			16.62	17.86
Nov. 16			14.40	14.26
Dec. 3		10.72	13.46	14.20
Jan. 3	10.69	10.82	14.16	14.89
Feb. 5	8.56	8.99	11.05	11.61
Mar. 4			10.35	10.03
Apr. 23			10.75	10.22

†16 metric tons of gypsum per hectare.

only a slight decrease was observed. Although the means varied over time, they are not statistically significantly different at the 0.05 level for any of the sample dates. The initial mean value of 24.56 calculated for the second season was much lower than the initial value of 47.00 calculated for the first season. This was because by Oct. 23 of the second season, the watershed had already experienced a rainstorm in which over eight cm of precipitation fell whereas the fall of the first season was dry.

In the evaluation of the time of gypsum application, no increases in aggregate stability were observed. This was for the two sampling dates which followed the time of reapplication at both sites.

It was quite evident during the determination of aggregate stability that the mechanism of breakdown involved entrapped air within the aggregate. Therefore, in addition to running the analyses on air dried aggregates, aggregates which were retained at their initial moisture content when sampling were also analyzed (Table VI). No differences due to gypsum treatment were discerned. The greatest decrease in stability with time of year was seen at the beginning of the season. Values absent in Table VI represent aggregates that withstood more than 100 drops and did not break down completely. The procedure was stopped at this point and the aggregates arbitrarily classified as stable. It took appreciably more drops to destroy the same amount of moist aggregates than aggregates that had been air dried. The greater stability of the moist aggregates reflect the importance of the wetting of an aggregate and subsequent air entrapment on its stability. The moist aggregates also exhibited a large degree of variability. This is in agreement with findings by Alderfer (1946). He attributed this to the variability in moisture content among the aggregates within a sample.

The previous discussion dealt with stability of an aggregate. Another property examined is size distribution of aggregates and mean size. This was evaluated using a water sieve method. Results are given as mean weight diameter (MWD), and geometric mean diameter (GMD) in Table VII, and percent recovered and size distribution on a weight basis in Tables VIII and IX.

At site E1, GMD and MWD did not correlate very well (r^2=.11). This is because the MWD puts more emphasis on the larger size class than GMD. The GMD accounts for the log normal distribution of aggre-

Table VI. Aggregate stability at various sites as determined by the water drop method using soil retained at its moisture content upon sampling, 1979-1980.

Date	E1 Treated†	E1 Check	E4 Treated	E4 Check
	Drops/0.10 gram of soil after which slaking stops			
Oct. 23				100.00
Nov. 6			51.40	50.60
Nov. 16			48.90	50.20
Dec. 3		17.94	23.90	21.80
Jan. 3	16.77	17.92	23.40	23.37
	Drops to destroy 0.10 gram of soil‡			
Feb. 5	49.96	50.48	49.46	54.16*
Mar. 4	----not tested--------		56.12	53.16

†16 metric tons of gypsum per hectare.
‡On dates prior to these, the aggregates tested withstood more than 100 drops and did not break down completely. These aggregates have been classified as "stable".
*Significant difference between treatments at the 0.05 level.

gates. Both GMD and MWD emphasize the larger aggregates as these are important in preventing erosion and maintaining infiltration. However, GMD puts more relative emphasis on the smaller aggregates than does MWD. At site E1 the distribution at the later dates is such that the aggregates are either very large (>8.00 mm) or dispersed (<0.50 mm). There was no significant difference in aggregate size distribution between treated and untreated soil for any of the dates sampled using either indices. However, the values for the untreated soil were higher for every sample date.

At site E4, MWD and GMD correlate very well, with r^2=.94. On nearly all dates samples were taken , there was a statistically signif-

Table VII. Geometric mean diameter (GMD) and mean weight diameter (MWD) of surface aggregates at various sites, 1979-1980.

Date	GMD		MWD	
	Treated†	Check	Treated	Check
Site E1				
Dec. 3		1.92		3.82
Jan. 3	1.90	2.12	3.97	4.19
Feb. 5	1.59	1.81	4.27	4.53
$MWD = 0.4715\ GMD + 3.32$			$r^2 = 0.11$	
Site E4				
Oct. 23		3.36		5.10
Nov. 6	2.38	2.88*	4.36	4.86*
Nov. 16	1.77	2.44	3.64	4.19
Dec. 3	2.37	3.41*	4.42	5.09*
Jan. 3	2.15	4.72*	4.26	6.36*
Feb. 5	2.88	4.85*	5.40	6.54*
Mar. 4	1.00	1.31*	2.48	2.97
$MWD = 1.0017\ GMD + 1.84$			$r^2 = 0.94$	

†16 metric tons of gypsum per hectare.
*Significant difference between treatments at the 0.05 level.

icant difference showing the untreated soil had a larger mean aggregate size.

The stable aggregate size distribution given in Tables VIII and IX shows that the untreated soil contained more aggregates than the treated soil in the > 8.00 and 8.00-4.70 mm size class in almost every sample for both sites. These larger aggregates are less likely to erode. The gypsum treated soil had more aggregates in the smaller size classes.

Table VIII. Stable aggregate size distribution of site E4 as determined by water sieve analysis, 1979-1980.

Date	Treatment	Weight fraction of aggregates in size classes						
		>8.0mm	8.0-4.7	4.7-2.0	2.0-1.0	1.0-0.5	<0.5	Percent recovered
Oct. 23	Check	.402	.192	.180	.066	.040	.120	88.0
Nov. 6	Treated†	.342	.149	.174	.072	.049	.214	78.6
	Check	.361	.225	.149	.051	.035	.180	82.0
Nov. 16	Treated	.270	.118	.172	.083	.052	.304	69.6
	Check	.284	.174	.203	.100	.055	.184	81.6
Dec. 3	Treated	.342	.163	.170	.064	.034	.229	77.1
	Check	.385	.211	.189	.064	.028	.124	87.6
Jan. 3	Treated	.335	.154	.151	.064	.039	.258	74.2
	Check	.673	.105	.086	.029	.015	.093	90.7
Feb. 5	Treated	.588	.063	.055	.031	.038	.226	77.4
	Check	.724	.081	.059	.026	.015	.095	90.5
Mar. 4	Treated	.155	.085	.128	.113	.096	.421	57.9
	Check	.201	.095	.154	.123	.095	.332	66.8

†16 metric tons of gypsum per hectare.

Table IX. Stable aggregate size distribution of site E1 as determined by water sieve analysis, 1979-1980.

Date	Treatment	Weight fraction of aggregates in size classes						Percent recovered
		>8.0mm	8.0-4.7	4.7-2.0	2.0-1.0	1.0-0.5	<0.5	
Dec. 3	Check	.247	.165	.187	.082	.050	.264	73.6
Jan. 3	Treated†	.289	.164	.156	.061	.034	.298	70.2
	Check	.301	.183	.163	.062	.032	.261	73.9
Feb. 5	Treated	.486	.023	.028	.029	.033	.401	59.9
	Check	.522	.022	.027	.025	.034	.371	62.9

†16 metric tons of gypsum per hectare.

The following explanation of trends through the season is based on laboratory observation and data. The discussion will pertain to site E4 (Fig. 7). From Oct. 23 to Nov. 16 the reduction of the larger aggregates was due to raindrop impact. After this, a subsequent increase in the mean diameter of aggregates up to Feb. 5 corresponded to the thickening of the surface crust. The thickened crust resisted breaking up from the action of water. Soil that did slake was of a fine particle size. On Mar. 4, there was a reduction in the $>$ 8.00 mm size class aggregates and a large increase in the $<$ 0.50 mm size class which is reflected in the lower GMD. Slight cracking and increased root growth weakened the crust. The sieving motion was then able to disrupt the crust and provide more surface area for soil particles to slake off. The gypsum treated soil retained a higher moisture content which created weakness in the crust. This was the reason for the lower MWD and GMD values obtained.

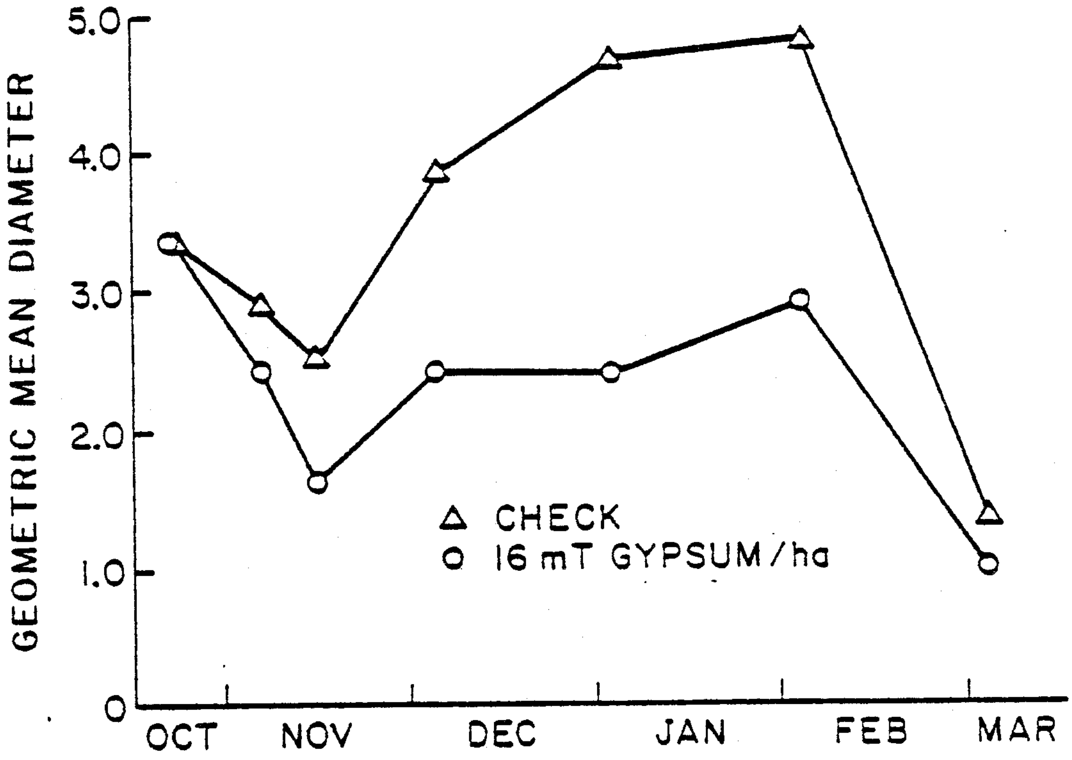


Figure 7. GMD as a function of treatment and time during the rain season at site E4, 1979-1980.

V. CRUSTING

1. Review of Literature

The formation of a crust on the soil surface has been mainly attributed to aggregate destruction following the impact of waterdrops during rainfall. The detached soil particles then wash into and fill the pores in the surface of the soil. A second mechanism, compaction of the surface by raindrop impact, has also been proposed. After rainfall there may be deposition of eroded soil with orientation of clay particles at the soil surface to further decrease permeability (McIntyre, 1958a). McIntyre states this last mechanism is not very important as it didn't decrease permeability in his measurements. Once the soil particles are rearranged, cementing between them may take place due to the increased surface area in contact between particles. Silica, amorphous sesquioxides, alumino silicates, and organic matter are all important cementing agents and have been reviewed by Uehara and Jones (1974).

The effects of crusting are generally adverse in agriculture. Reduced seedling emergence for many species of crops have been shown to be a result of crusting (Hanks and Thorpe, 1957; Hadas and Stibbe, 1977; Stout et. al., 1961; Bennett et. al., 1964). Reduced infiltration resulting in increased runoff has also been attributed to crusting of the soil surface (Edwards and Larson, 1969; Hillel and Gardner, 1969; Duley, 1939). The mechanism by which infiltration is reduced is primarily through the reduction of number and size of pores. Some reduction in infiltration may be due to entrapped air since a surface crust exists (Slater and Byers, 1931). However, VanBavel (1951) and Domby and Kohnke (1956) show crusting has almost no effect on air movement unless it is completely impervious or is very wet. Duley (1939) states that the crust is the main factor in controlling infiltration on the soils he studied.

Practices to reduce crusting involve, 1) the reduction of raindrop impact by use of a vegetative cover or mulch, or 2) the mechanical breakup of an existing crust, or 3) to reduce the destruction of soil aggregates by the use of amendments. Bennett et. al. (1964) used gypsum as an amendment in reducing crust strength and obtained favorable results. This was attributed to the increased moisture content of the crust treated with gypsum. Soil crusts are much weaker with increasing moisture content (Kemper et. al., 1975).

The strength of the crust is measured primarily by determination of the modulus of rupture. This is the most popular method and is described by Richards (1953) and Allison (1923). Soil penetrometers have also been used to measure crust strength (Tackett and Pearson, 1965). Since the formation of a crust at the early stages is very thin, measurement of the thickness can be obtained by the use of thin sections. This method has also been used to evaluate the porosity (Tackett and Pearson, 1965; McIntyre, 1958b; Evans and Buol, 1968; Wilkens et. al., 1977).

2. Materials and Methods

Crusting of the soil surface was documented by the use of thin sections. Crust thickness was measured and porosity evaluated to ascertain any differences between treated and untreated soil. Sampling was conducted on several dates during the winter rain season when observable changes had occurred in the soil surface.

Samples were taken with aluminum cylinders eight cm in diameter and seven cm long. The cylinder was inserted into the ground and the soil removed from around and below the cylinder to free it from the soil body. The samples were placed in plastic containers for transport and stored in a cooler. In the preparation, the sample was air dried and the cylinder cut away and removed. Excess soil was removed and the sample placed in a paper cup. Samples were impregnated with "Clear Lite", a clear polyester casting resin mixed with an appropiate amount of methyl-ethyl-ketone hardener. The samples were processed under a vacuum to insure complete impregnation. The sample was removed from the vacuum and placed in an oven at 60°C for 48 hours to complete hardening. All operations that involved the resin were conducted under an exhaust hood.

Once the sample had hardened, a cross section four to five mm in thickness was cut using a diamond lapidary saw. One side was smoothed using a lapidary wheel with successively finer 240, 400, then 600 grit silicon carbide powder. The smooth side was mounted on a glass slide with epoxy and heated to complete bonding. The sample was lathed down to a thickness of 20 microns through the courtesy of the Geology Dept. at OSU. The finished slides were observed and photographed for differences in crust thickness under a petrographic microscope.

3. Results and Discussion

No observable differences in porosity or thickness of the crust could be discerned between samples from the treated and untreated soil. The formation of the crust was rapid and occurred with the first rains. As the season progressed the crust thickened slightly (Table X). Site E1 had the thickest crust as well as the least stable aggregates (Table IV, V). Site E3 also had a thick crust by the end of the season, but this site was in a perennial grass field and had a crust existing at the beginning of the season. Site E4 had a thinner crust than E1 due to the more stable aggregates at site E4. The more stable aggregates of site E4 as determined by the water drop method is also inferred here. The aggregates at site E4 at the beginning of the season (Plate 7) are more distinct and angular than those at site E1 (Plate 4).

The formation of a crust was rapid in rill areas. This is illustrated in Plate 1 which was taken on Oct. 29, 1980, following the first rainstorm after planting. The deposition in the rills produced a smooth surface by the end of the season (Plate 3). Plates 4-9 show thin sections of the crust at sites E1 and E4 for various dates during the season. A rapid crust formation was observed from Nov. 15 (Plate 7) to Dec. 22 (Plate 8). By the end of the season the growth of the wheat and wetting-drying cycles resulted in an increase in porosity.

Table X. Thickness of crust at various sites, 1978-1979.

Date	Thickness of crust mm		
	E1	E3	E4
Nov. 15	0	2-3	0
Dec. 22	2-5	2-4	2-3
Jan. 21	3-5	2-5	2-4
Feb. 4		3-5	
Mar. 9	3-8		3-5
May 4	5-10	5-10	3-6

Most of the formation of a crust has been attributed to dispersion of aggregates, clogging of pores, and the beating action of raindrops (McIntyre, 1958a). However, at this watershed it seems that much of the thickening of the crust can be attributed to sedimentation from erosion upslope. This is best illustrated in Plate 5 where the stratification indicates deposition of several cycles. The effect of the deposition process is also indicated by the fact that the original gypsum application made on Oct. 23, 1980 was observed to be buried under several mm of soil at the end of the season.

Gypsum did exert an effect on the crust by making it weaker. The crusts from the gypsum treated soil had an appreciably higher moisture content (Table III) than the crusts from the untreated soil in the second season when an application of 16 metric tons per hectare was used. Although measurements of crust strength was not conducted, this condition was inferred by two other results; the water sieve analysis for water stable aggregate size distribution (Tables VIII, IX), and sed-

Plate 1. Surface condition at site E4 on Oct. 29, 1979, following first rainstorm after plowing. Note rill crust formation.

Plate 2. Surface condition at site E4 on Feb. 24, 1980. Note surface smoothness.

Plate 3. Surface condition at site E4 on Apr. 23, 1980. Note smoothness of surface and lack of plant residue from crust formation and sedimentation of eroded soil.

iment yield from infiltration trials (Table XIV). A weaker crust will yield more sediment as the soil particles are more easily detached. The water sieving analysis presented a visual observation of a weaker crust. When a pronounced crust had formed, water sieving was done by placing the entire crust upon the top sieve. The crust from the treated soil broke up and dispersed much more readily than the crusts from the untreated soil. The results of a weaker crust due to the application of gypsum is in agreement with findings by Bennett et. al. (1964). Bennett et. al. attributed this to the decreased evaporation because of the white color. It is suggested here that the increase in moisture was brought about by the affinity for water by the gypsum, or a change in

Plate 4. Thin section of soil surface at site E1 on Nov. 15, 1978. Note the porous nature. Image: 2 x 3 mm.

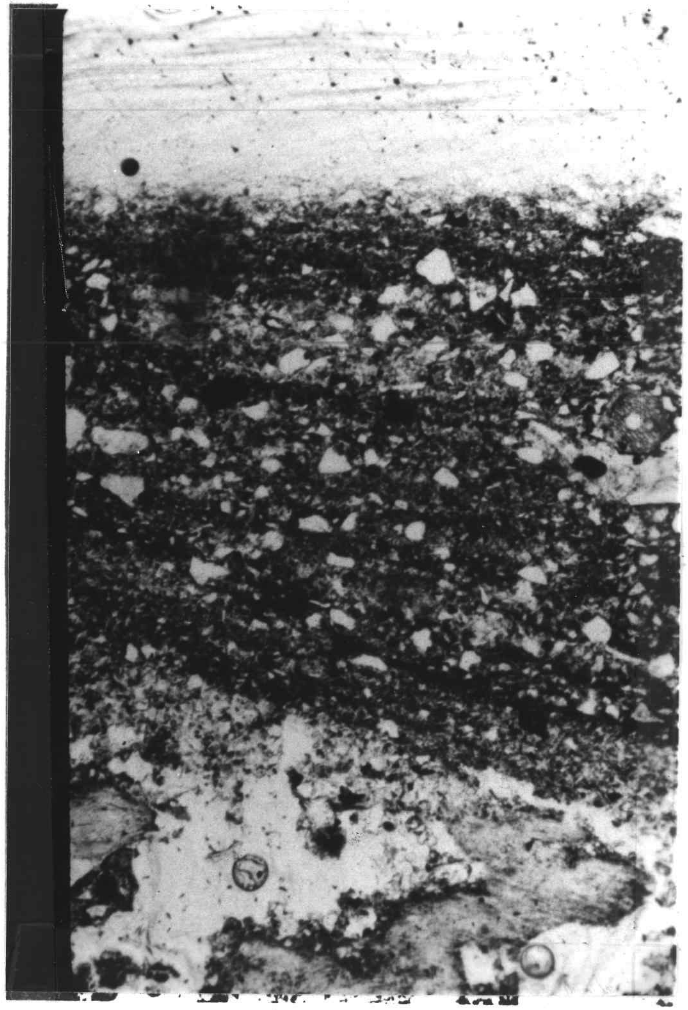


Plate 5. Thin section of soil surface at site E1 on Mar. 9, 1979. Note the layering indicating several cycles of deposition. Image: 2 x 3 mm.

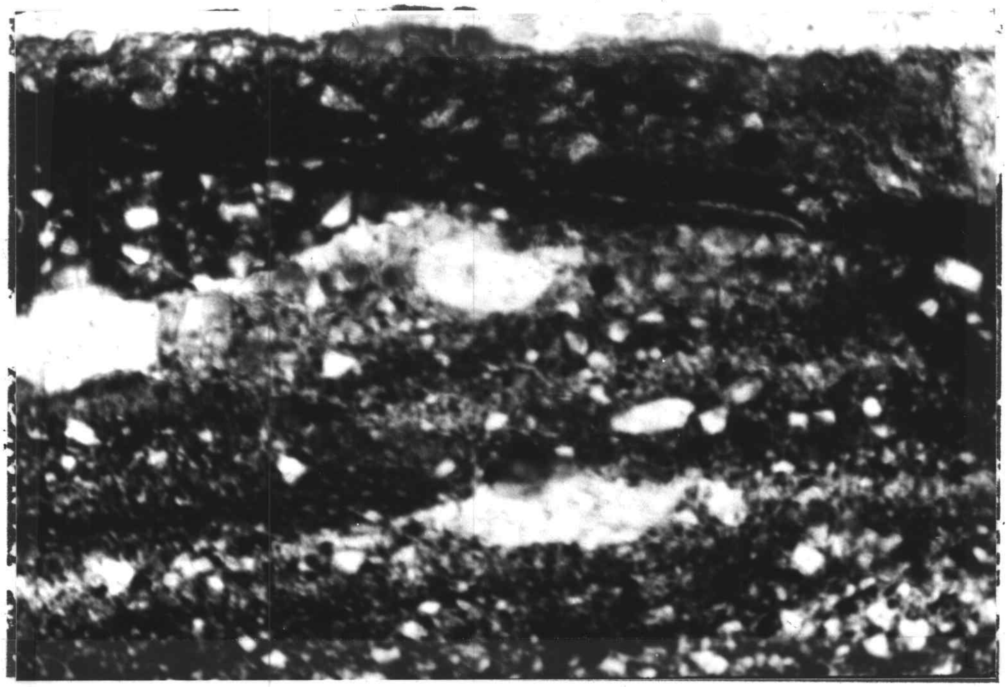


Plate 6. Thin section of soil surface at site E1 on May 4, 1979. Note layering which is broken up possibly from root penetration and/or wetting-drying cycles. Image: 3 x 2 mm.

the porous matrix which resulted in more water being retained. Gypsum may have usefulness where crusting reduces seedling emergence, however, it does not seem to have positive effects on reducing erosion through its influence on crusting.

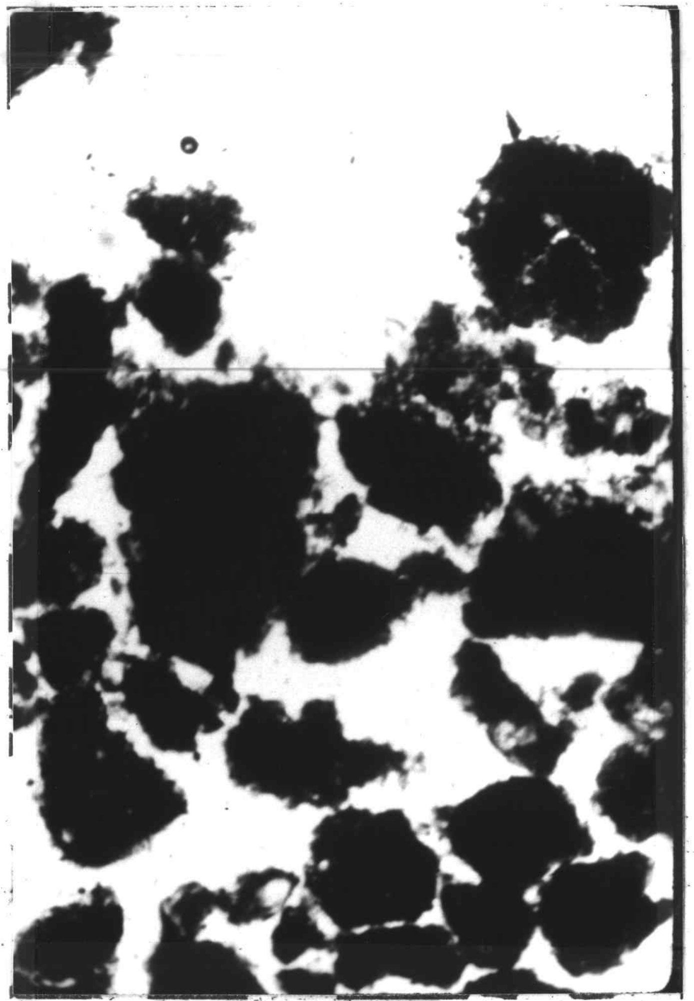


Plate 7. Thin section of soil surface at site E4 on Nov. 15, 1978. Note the porous nature and angular nature of aggregates in relation to site E1. Image: 2 x 3 mm.

Plate 8. Thin section of soil surface at site E4 on Dec. 22, 1978. Note the crust formation since Nov. 15, 1978 (Plate 7). Image: 2 x 3 mm.

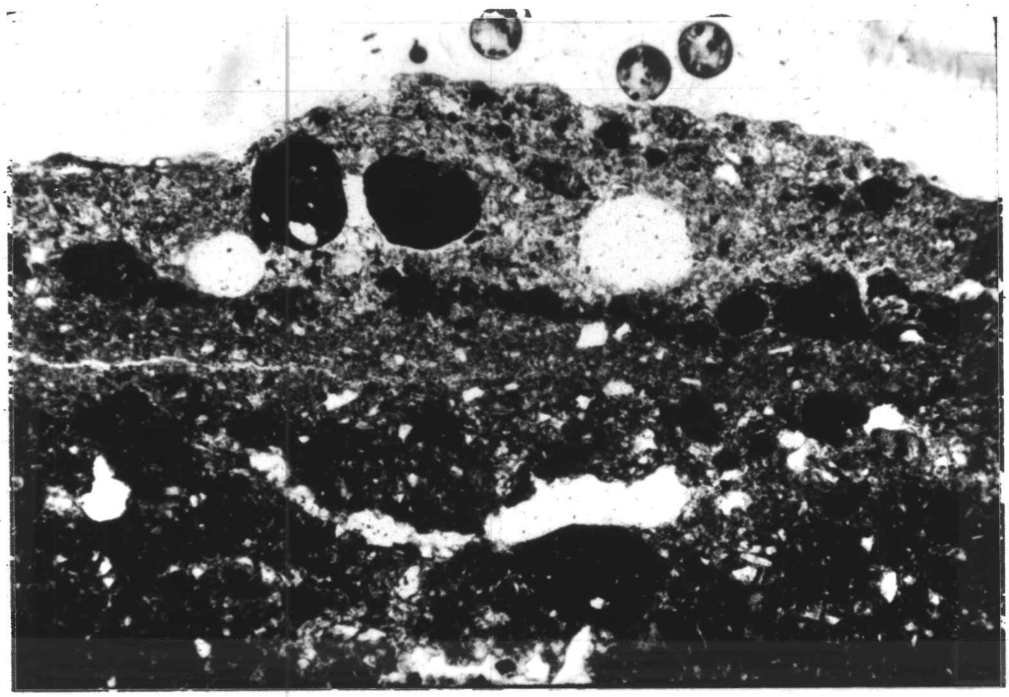


Plate 9. Thin section of soil surface at site E4 on May 4, 1979. Crust is broken up possibly from root penetration and/or wetting-drying cycles. Image: 3 x 2 mm.

VI. RUNOFF AND EROSION

1. Review of Literature

Measurement of soil erosion on a localized scale can be done by two methods. One is by measuring the changes in the soil surface level, and the second method is by measuring the soil caught in a catchment basin from a plot area. There are several ways by which to detect surface level changes (Gleason, 1957). The accuracy of these methods is very poor. On a 100 m^2 plot, one mm of surface change corresponds to 15,000 kg/ha of soil. Measuring the soil caught in a basin from this same area, 0.1 kg of soil represents a soil loss of ten kg/ha (Hudson, 1971). Compounding the inaccuracy of measuring soil level changes is the fact that rainfall can compress the soil after it has been recently plowed. A reduction in the surface level would be due to compression and not necessarily erosion. For research purposes erosion plots are most often used.

The first experiments using plots were started by the Forest Service in Utah in 1915 , followed by those of Professor Miller in Missouri in 1917. The design of the plots vary in relation to the objectives and nature of the experiments. Size depends largely on the treatment under investigation. The smallest plots, one to two m square, are useful when large numbers are needed for preliminary investigations, or for simple comparisons such as a yes-no effect of treatment with soil amendments (Hudson, 1971). The accuracy of small plots is suitable for establishing relative erodibility between treatments, but not suitable for sampling soil loss from larger catchments (Hayward, 1969). For sampling soil loss from larger catchments, longer plots are needed so that the cumulative effect of runoff increasing down the slope is produced. The length depends on the sampling purpose. A standard arbitrary length of 22 m is used in the United States for comparative purposes. If one is testing for erosion losses with the use of terraces, plot lengths should correspond to the length between terraces. Larger plot areas will increase the amount of runoff and may need large storage tanks or mechanical division of the runoff. Plot boundaries can be made of strips of metal, wood, or other material which prevent the passage of water into or out of the plot. Troughs to collect the runoff should be built with a steep gradient to prevent deposition of eroded soil and covered to exclude rainfall (Hudson, 1971).

2. Methods and Materials

Erosion plots with boundaries made of galvinized steel and measuring one m square by 0.15 m high were used at all three study sites. During the first rain season four plots were placed side by side at each of the two midslope sites, E1 and E4, in the main study area of the watershed. Two plots were placed side by side in the perennial grass field at site E3. These plots were eliminated after the first season. It was felt no further study was needed as runoff and erosion were slight at this site. The plots at site E1 were also eliminated after the first rain season as the farmer failed to plant this subwatershed.

A collection trough which collected the runoff and channelled it into a PVC pipe was inserted into the plot wall on the downslope side. The pipe, measuring three m long by 2.54 cm in diameter, ran downslope and emptied into a collection tub. The tub was partially set into the ground and covered with a plastic lined wooden top. The pipe emptied into the tub through an opening in the top using a 90° fitting which was sealed with caulking. This allowed only the runoff water to enter the tub and also minimized evaporation. A construction brick was placed atop each tub cover to eliminate movement by wind. A cover was installed over the collection trough.

Daily measurements were made of the amount of runoff the first rain season. The depth of water in the tub was measured using a tape measure. These measurements were converted to volumes. Sampling for sediment concentration in the runoff was done by grab sampling when an appreciable amount had been collected in the tub. After sampling, the tubs were emptied. During the second rain season, measurements of the amount of runoff were made when sampling during interstorm periods. A graduated cylinder provided a much more accurate measurement of runoff, especially at low amounts. Sediment concentration in both seasons was determined from duplicate subsamples. A known volume of runoff was taken to dryness in an oven at 105°C and weighed. Knowing the amount of runoff, rainfall, and sediment concentration in the runoff, relative runoff and erosion amounts were calculated. Duplicate plots were used the first season at sites E1 and E4, and the average used for determination of runoff and erosion.

In addition to the measurement of runoff and sediment yield from erosion plots, these measurements were also made when the infiltration trials were conducted. Sediment concentration values were analyzed for differences between treated and untreated soil, and changes with time over the test period and season. Total sediment yields and concentrations for the entire infiltration test were calculated to assess differences between treated and untreated soil.

Calcium content of the surface soil (extractable Ca using sodium acetate), vegetative yields, and saturated hydraulic conductivity (K) (Klute, 1965) of subsoil layers were analyzed to determine possible mechanisms for differences between treated and untreated soil. Soil cores were tested for K with distilled water and then saturated with a .02 N $CaSO_4$ solution and again tested for K using this solution. The same cores were used following the initial determination of K because of the extreme variability found between cores of the same horizon.

3. Results and Discussion

The previous discussion dealt with some of the factors that effect runoff and erosion. The data indicate that the gypsum treated soil exhibited slightly lower infiltration when a rate of 16 metric tons per hectare was used. However, the final test for the treatment effects is on actual runoff and erosion from field plots. Results for runoff during the first rain season are given in Fig. 8, 9, and 10. The values are averages of two replications for treated and untreated plots at sites E1 and E4.

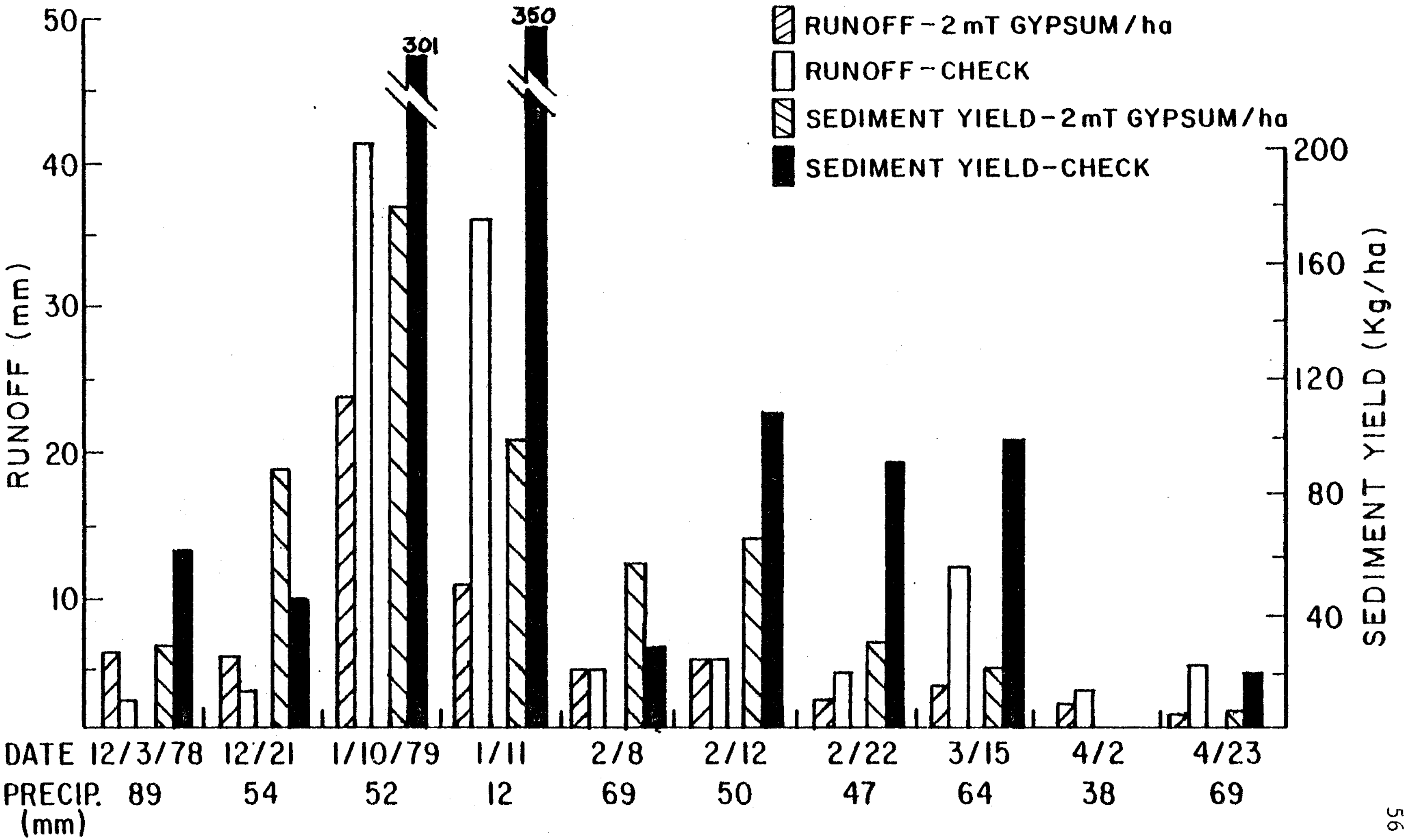


Figure 8. Precipitation, runoff, and sediment yields from erosion plots at site E1, 1978-1979. Precipitation data are cumulative for the sample period.

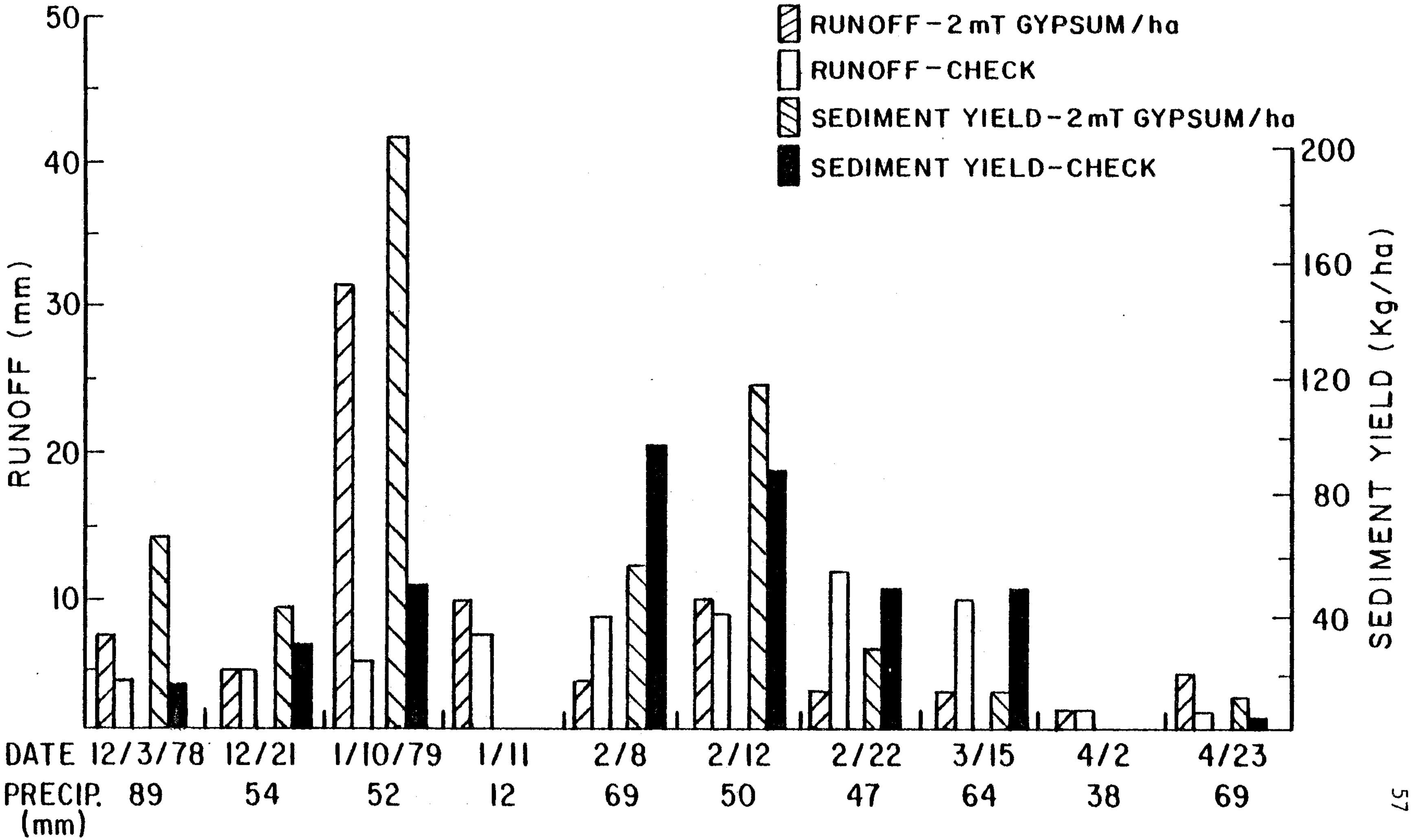


Figure 9. Precipitation, runoff, and sediment yields from erosion plots at site E3, 1978-1979. Precipitation data are cumulative for the sample period.

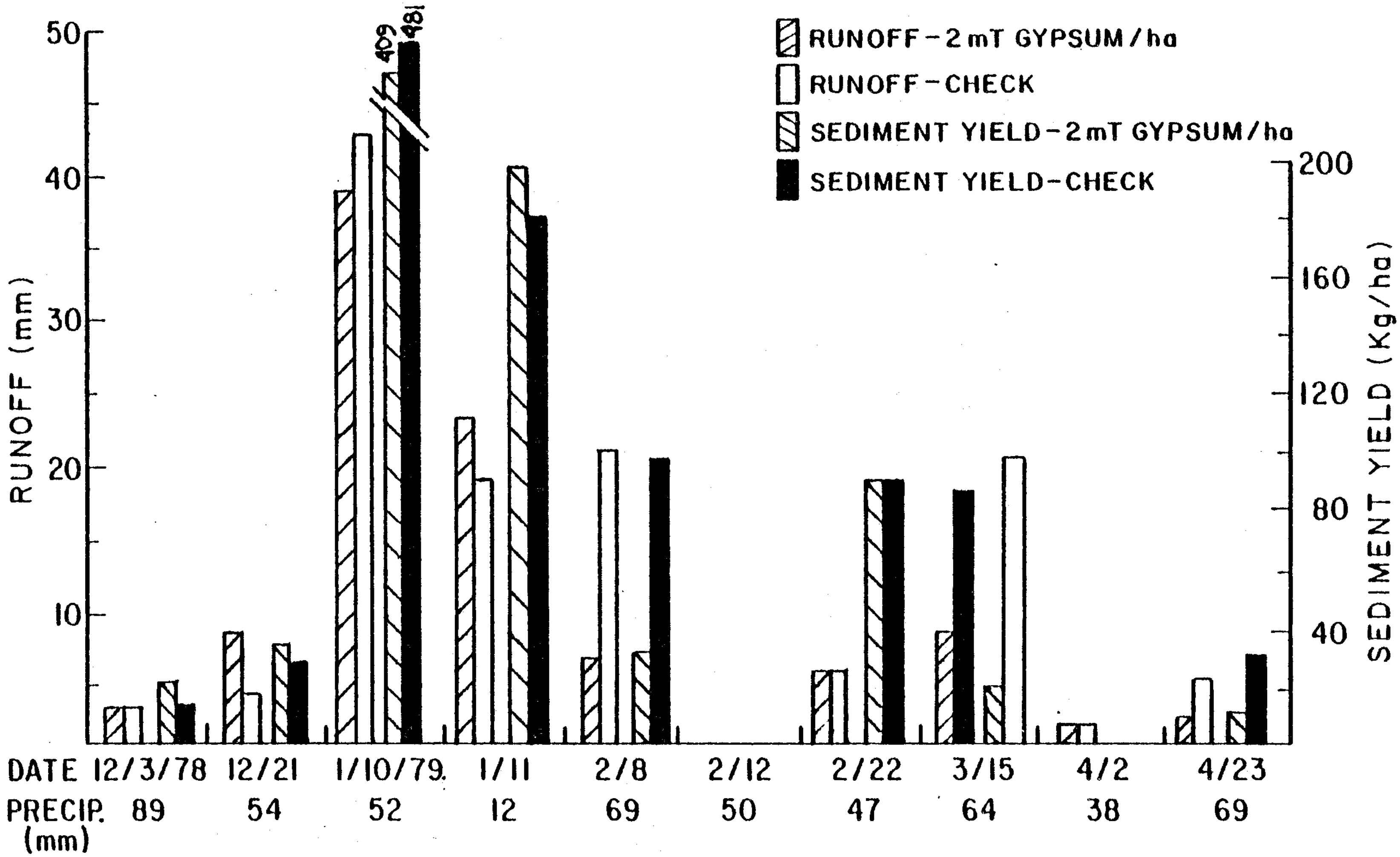


Figure 10. Precipitation, runoff, and sediment yields from erosion plots at site E4, 1978-1979. Precipitation data are cumulative for the sample period.

Extreme variability existed between replications and the results are inconclusive as to the affects of the treatment. Much of the variability may be due to small plot size. Some of it may be due to the freezing period just prior to Jan. 10. Freezing may have changed the microrelief within the plots.

Whereas differences due to treatment can not be discerned, trends over the season are evident. These trends are similar for all three sites. At the beginning of the season the soil was dry and the surface porous. The resultant runoff was low. With each successive sample date the relative amount of runoff increased with a maximum of over 100% on Jan. 11. Freezing occurred in early January and the resultant runoff on Jan. 10 was high. The greater than 100% runoff was due to seepage from uphill transient water. Following this date there was a reduction in the relative runoff. This reduction reflects both the drying of the soil profile and the cracking of the soil surface. The sediment yield follows closely the pattern of the runoff; as runoff increased, sediment yield increased.

During the second rain season, much less variability existed between plots. This is a result of the reduced runoff that occurred (Fig. 11). Whereas no differences can be discerned between treatments, some trends do exist. With the exception of the sample period prior to Nov. 26, the greatest amount of runoff and erosion occurred during the periods from Jan. 9 - Jan. 18, and Jan. 18 - Feb. 19. This was due to the surface crust and high water tables which existed during this time. The data for the sample period ending Nov. 26 are unexplained. The increased runoff at the start of the second season

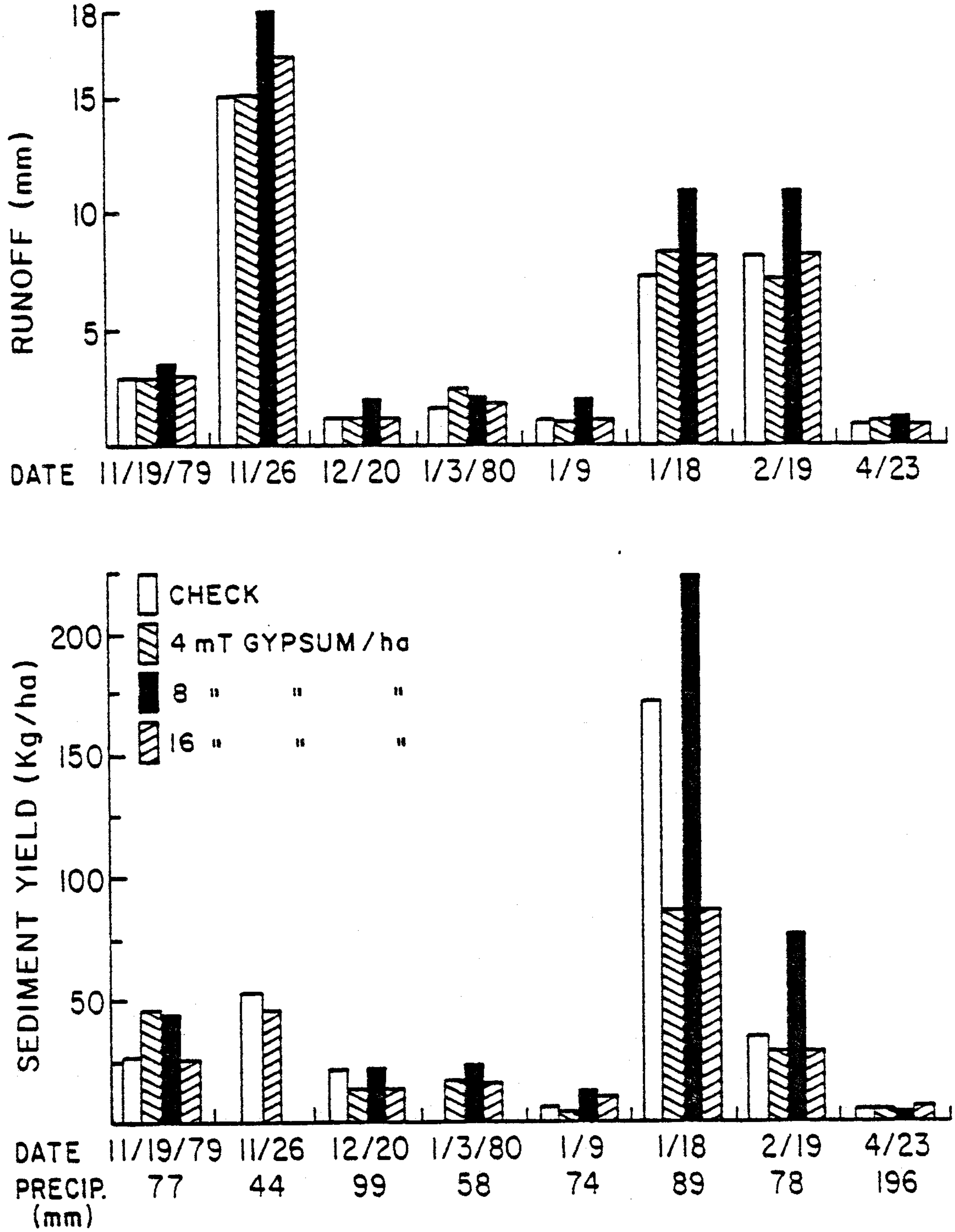


Figure 11. Precipitation, runoff, and sediment yields from erosion plots at site E4, 1979-1980. Precipitation data are cumulative for the sample period.

compared to the first season was due to both the formation of a crust created by a rainstorm in late October, and lack of a vegetative cover. The collection periods up to Jan. 18 were low in runoff due to the lower water tables and moderate storms. Under our conditions, much of the runoff that occurs is preceded by long storm periods of low to moderate intensity which build up a water table. The reduction of runoff following Feb. 19 was postulated to be a result of an increase in vegetative cover. The second sampling season had a much better crop cover by this time period than the first season. The importance of crop cover on reducing erosion has been well documented and is regarded as one of the most important factors in controlling erosion.

The amount of crop cover largely explains the differences between plots. At the beginning of the season the untreated plot was observed to have the greatest amount of crop cover. Much of the growth was due to grasses other than wheat. Runoff and erosion were relatively low for this plot for the first two sample periods. After Nov. 26, the area was sprayed with a herbicide. The untreated plot lost much of its vegetative cover and the sediment yield increased appreciably. The plot which was treated with eight metric tons of gypsum per hectare was noted to have a poor stand of wheat. The reduced cover resulted in this plot yielding the greatest amount of sediment. The untreated plot had a better stand of wheat than the plot treated with eight metric tons of gypsum per hectare but much less than the four or 16 metric tons per hectare treatment. The differences in crop cover during the rain season were inherent from the planting regime of the farmer.

An estimation of the crop growth was made at the end of the season to determine the effects of the treatments. However, such results can not be related to relative crop cover between plots during the rain season. This is because much of the growth of the wheat does not occur until spring when the greatest potential for erosion has passed. Crop growth may provide additional insight into the investigation of the problem and therefore was evaluated. The results of vegetative yield in response to gypsum treatment for both seasons are given in Table XI. No statistically significant differences between treatments could be determined for the first season. For the second season, little difference existed between the untreated and two lower application rates. A substantial increase in yield was seen for the highest rate of application. The increased yield may be due to the high rate of application, or it may be due to the time of application. A reapplication of 16 metric tons of gypsum per hectare was made on Feb. 24, 1980. After this period, growth of the wheat begins again. Reapplication may be necessary as much of the calcium from the gypsum has moved out of the soil either by erosion or transport into the subsoil with infiltrating water as will be pointed out later. Some of the gypsum was noted to leave the plot with the runoff when infiltration trials were conducted.

Tables XII and XIII show the values of extractable calcium for several dates at all sites for treated and untreated soil. For the second season of testing, only the highest rate of application was tested in comparison with the untreated soil. During the first season,

Table XI. Vegetative yield at various sites as of June 7 as affected by treatment.

E1		E4	
Treatment†	Yield‡	Treatment	Yield
	kg/m^2		kg/m^2
1978-1979			
2	.53	2	.81
0	.54	0	.74
1979-1980			
		16	1.31
		8	.66
		4	.74
		0	.71

†Metric tons of gypsum per hectare.
‡Based on oven dry weight of total above ground vegetation.

the seasonal trend was similar at all three sites. There was a gradual reduction in calcium content of the treated soil until spring when the values are nearly the same as the untreated soil. In the second season there was also a gadual reduction in the calcium content of the treated soil. The largest reduction was from Jan. 3 to Feb. 5. This relates closely to the period of greatest sediment loss, which implies that the gypsum was either being moved off in the runoff, or the adsorbed calcium was moved off with the sediment. Visual observation showed much of the gypsum undissolved, so it appears that the gypsum was being eroded. A reapplication of gypsum at the rate of 16 metric tons per hectare made on Feb. 24 at site E4 raised the value of extractable calcium from 14,300 to 49,980 kg/ha. One half of this was moved out of the upper soil by Apr. 23.

Table XII. Calcium content† in surface soil‡ at various sites, 1978-1979.

Date	E1 Treated§	E1 Check	E3 Treated	E3 Check	E4 Treated	E4 Check
	-----kg/ha-----		-----kg/ha------		-----kg/ha------	
Nov. 15		3,300		3,800		2,400
Dec. 22	3,900	2,600	4,550	3,800	3,100	2,500
Jan. 21	2,700	2,300	4,150	3,600	2,920	2,580
Feb. 8	2,000	2,600			2,900	2,300
Mar. 10	2,020	2,200	3,800	3,650	2,750	2,600

†Extractable calcium using sodium acetate.
‡Upper two cm of soil.

§Two metric tons of gypsum per hectare

Whereas the affects of gypsum were not discernible with the use of erosion plots, definite differences between treated and untreated soil existed for runoff and sediment yield on the infiltration plots. The higher moisture content of the surface soil on the gypsum treated plots contributed to higher sediment yields during the second rain season (Table XIV). Part of this may be due to the increased amount of runoff from the treated soil. Average runoff concentrations reflect the relative erodibilities for the treated and untreated soil. The concentration of sediment was appreciably higher in the runoff from the treated soil. The values of runoff concentration vary between dates during the rain season. On the gypsum treated plots the soil was most erodible at the beginning of the season and decreased with time until late

Table XIII. Calcium content† in surface soil‡ at various sites, 1979-1980.

Date	E1		E4	
	Treated§	Check	Treated	Check
	------kg/ha------		--------kg/ha------	
Oct. 23				2,640
Nov. 6			31,500	2,400
Nov. 16			36,500	2,800
Dec. 3		2,130	30,900	3,400
Jan. 3	34,800	2,640	26,400	2,400
Feb. 5	5,390	2,300	14,300	2,300
Mar. 4			49,980¶	2,580
Apr. 23			24,150	2,360

†Extractable calcium using sodium acetate.
‡Upper two cm of soil.
§16 metric tons of gypsum per hectare.
¶Reapplication of gypsum on Feb. 24 at the rate of 16 metric tons per hectare.

in the season. The high value of 2.8 g/L on Oct. 29 was attributed to some of the gypsum moving off the plot in the runoff. During the infiltration trials at the earlier dates, gypsum could be seen moving off the plot in the runoff. An increase in sediment concentration late in the season was due to the formation of a crust. In a saturated state any additional rainfall is much more apt to detach soil particles from the crust. On the untreated soil the sediment concentration in the runoff was essentially equal for the first two dates. Sediment concentration values increased as the season progressed due to the formation of a crust.

The graph of sediment concentration versus time during a given infiltration test was similar in shape for both treated and untreated

Table XIV. Sediment, runoff, and sediment concentration from infiltration trials at site E4, 1979-1980.

Date	Sediment yield		Runoff		Total	Concentration	
	Treated†	Check	Treated	Check	applied	Treated	Check
	----grams/plot----		---------liters/plot---------			---grams/liter---	
Oct. 29	8.4	2.8	3.00	2.84	10.53	2.80	0.98
Nov. 16	4.1	1.5	1.59	1.60	8.35	2.58	0.94
Dec. 3	3.4	2.7	2.35	2.45	9.08	1.45	1.10
Jan. 15	5.4	3.8	2.97	2.82	6.53	1.82	1.35
Feb. 5	4.5	7.3	3.25	3.02	8.35	1.38	2.42
Mar. 4	9.4	4.8	3.09	2.81	9.80	3.04	1.71

†16 metric tons of gypsum per hectare.

soil and between seasons. A representative curve is given in Fig. 12. The curve shows a high initial sediment concentration as the runoff transported the loose, available soil particles. This decreased with time as the source of easily erodible soil was lessened. After a period of time the sediment concentration increased due to the saturation of the soil.

Although much of the gypsum loss is postulated to have left via erosion, some movement of calcium downward into the subsoil may have occurred. If this was the case it may increase the hydraulic conductivity of the less pervious subsoil layers. The results of the effects of $CaSO_4$ on K of two subsoil horizons at sites E1 and E4 are given in Table XV. At site E1 the $CaSO_4$ treatment increased the K for the B horizon but not for the C horizon. At site E4, no change was observed due to the $CaSO_4$ treatment in the B horizon. An increase in K was noted in the C horizon for both samples with the $CaSO_4$ treatment. Whereas the $CaSO_4$ treatment did increase the K, the relative increases are slight. It is not felt that these increases are of the magnitude that would reduce runoff and erosion.

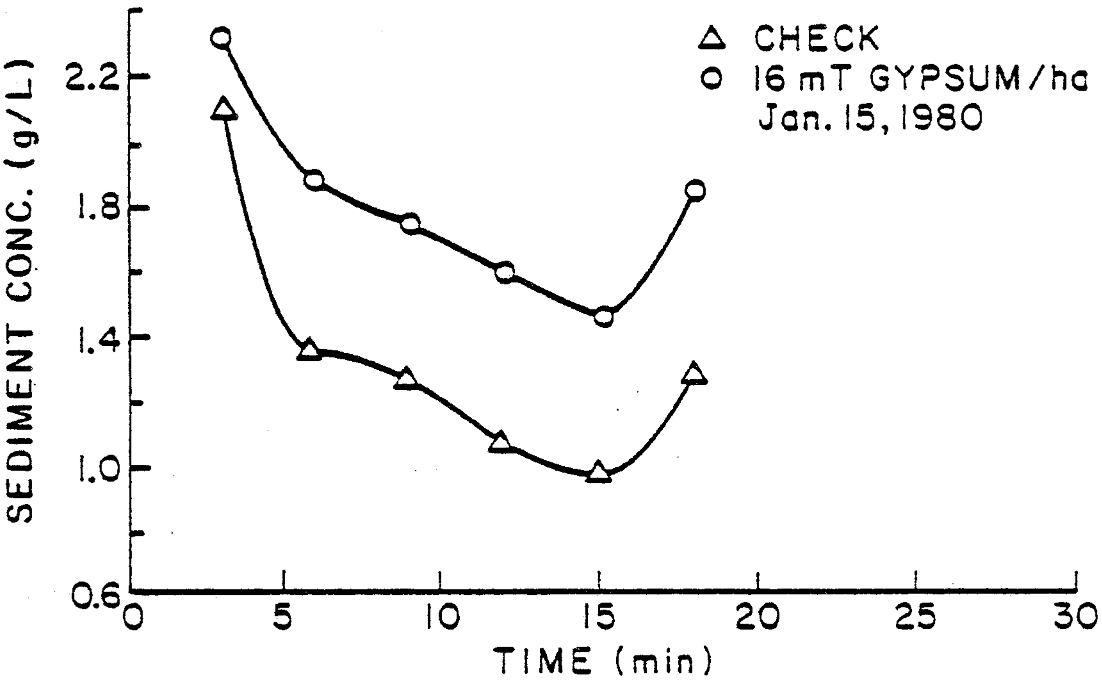


Figure 12. Sediment concentration in runoff from infiltration plots.

Table XV. Subsoil saturated K† as effected by treatment.

Sample	Core no.	Treatment	K	Db
			---cm/hr---	g/cm^3
		Site E1		
IIB_{2tb}	a	Check	4.88	1.48
	a	Treated‡	5.60	1.48
	b	Check	5.87	1.31
	b	Treated	6.02	1.31
IICr	c	Check	0.39	1.43
	c	Treated	0.32	1.43
	d	Check	1.43	1.31
	d	Treated	1.30	1.31
		Site E4		
IIB_{2tb}	e	Check	23.47	1.29
	e	Treated	23.44	1.29
	f	Check	4.08	1.28
	f	Treated	3.88	1.28
$IICr_1$	g	Check	2.86×10^{-3}	1.32
	g	Treated	3.53×10^{-3}	1.32
	h	Check	13.60	1.26
	h	Treated	17.30	1.26

†As determined using the constant head method (Klute, 1965).
‡.02N $CaSO_4$ solution used to saturate sample and in permeating solution.

VII. SUMMARY AND CONCLUSION

No effects on infiltration, crusting, aggregate stability, or runoff and erosion were observed with the application of gypsum during the first rain season. Trends over the season, regardless if treated or not, were distinct for all the phenomena studied. Infiltration values were initially high with a delayed time for runoff to begin at the beginning of the season. Values and time for runoff to occur decreased over the season until spring when the infiltration values increased to the levels found at the onset of the season. This was due to the cracking of the soil surface which conducted water down into the soil profile. The formation of a crust was observed to occur with the first few rains with subsequent rainfall thickening the crust by deposition of eroded material from upslope. Maximum crust thickness was observed at site E1 which also had the least stable aggregates. As a result of these studies it is concluded that the application of gypsum did not reduce the crusting tendency of the soil in either thickness or porosity. It is postulated that the gypsum did create a weaker crust by increasing the moisture content of the soil. Statistical differences of aggregate stability were discerned for a few samples at the three sites, but showed no relationship to treatment. Differences were slight and not of the magnitude which would help prevent crust formation and control erosion. The greatest reduction in aggregate stability occurred with the first rains with no change until spring where a slight increase was recorded. It was concluded that the application of gypsum did not maintain nor increase aggregate stability. The variability in erosion plot data was too great to permit relative comparisons between treated and untreated soil. Runoff and erosion was slight at the onset of the season due to the porous soil surface and its low moisture content. The greatest runoff and erosion occurred when a rainstorm fell on frozen ground. Runoff and subsequently erosion were minimal at the end of the season due to the cracking of the surface crust.

In the second season, application rates were increased from 2 to 4, 8, and 16 metric tons per hectare. The higher rates were applied in response to the negligible results obtained the first season. Infiltration values were lower for the treated soil due to the increased moisture content. Trends through the season were similar to those obtained the first season. Infiltration rates increased earlier in the spring due to a more vigorous wheat stand the second season. Sediment concentration and sediment yields were substantially higher on the treated soil for the infiltration trials. This was a result of a weaker crust due to the greater moisture content of the treated soil. Rainfall is more apt to detach soil particles from the crust and transport it in the runoff. It was concluded that the gypsum treated soil was more erodible than the untreated soil. Aggregate stability showed no statistical differences between treated and untreated soil for any of the sampling dates at sites E1 or E4 when using air dried soil. In addition, the analyses were conducted on samples retained at their field moisture contents when sampled. Absolute values increased as did the variability. This indicates that the penetration of water and air entrapment is an important mechanism in the breakdown of soil aggregates.

In the analyses of water stable aggregate size distribution, the untreated soil showed statistically significant higher values for MWD and GMD for nearly all of the sample dates. This was observed to be a result of the weaker crust of the treated soil. The crust of the treated soil readily broke up upon agitation when immersed in water, whereas the crust from the untreated soil remained relatively stable. Both treated and untreated soil showed a large reduction in the MWD and GMD at the end of the season due to root growth and penetration, and cracking of the crust which provided planes of weakness in the crust. The reapplication of gypsum in midseason had no effect on either MWD or GMD. Runoff and erosion showed no effects of treatment, but followed closely the pattern of crop growth. At the beginning of the season, the formation of a rill crust due to an early rainstorm produced runoff much earlier than the first season. Values were low for much of the season as the growth of wheat was much stronger than the first season. Differences in wheat growth between plots was due to planting and masked any differences that may have been created by the treatments.

One explanation for increases in aggregate stability may be replacement of monovalent ions by calcium ions without an increase in surface charge density. The physical effect of a large application of gypsum was also scrutinized. It is postulated that the physical effects predominated in an adverse way for erosion control. The gypsum was applied at the surface as this is where the breakdown of aggregates and formation of a crust occurs. In doing so it did not react completely with the soil. Besides the chemical nature of increasing aggregate stability, a physical means of bringing the soil particles together is needed. The gypsum was fairly inert and was subsequently eroded out of the plot area or buried from eroded soil. This created a layer of gypsum which provided planes of weakness in the crust. Subsequent erodibility of the soil was increased. The heaviest application of gypsum did increase wheat yields, but the increased growth took place after the potential for erosion had passed. Gypsum can increase the permeability of some subsoil horizons, but was not found to be of the magnitude that would reduce erosion.

In conclusion, the use of gypsum at low application rates didn't effect the properties of the soils studied due to removal by erosion before it was incorporated. An application rate of 16 metric tons per hectare was observed to have an adverse affect on erosion control by creating a weaker crust which is more susceptible to erosion. Gypsum may have beneficial effects in areas where seedling emergence is restricted by crusting, and it may increase wheat yields, but not enough information was obtained for recommending its use in this capacity. It is not recommended that gypsum be used to control erosion in Western Oregon under the conditions encountered in this study.

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APPENDIX

Appendix I
Soil Profile Descriptions

1. Site E1

Ap 0-33 cm, yellowish brown (10YR5/4) silt loam, dark yellowish brown (10YR3/4) when moist; moderate medium granular structure; abrupt smooth boundary.

IIB_{2tb} 33-56 cm, dark yellowish brown (10YR4/4) when moist silty clay loam; moderate fine to medium subangular blocky structure.

IICR	56-82 cm	
	82-89	
	89-130	Highly laminated soft siltstone and
	130-158	fine sandstone gently dipping to the
	158-174	east with zones of iron accumulation.

2. Site E3

Ap 0-26 cm, grayish brown (10YR5/2) silt loam, very dark grayish brown (10YR3/2) when moist; moderate medium granular structure; common medium roots; many medium pores; clear smooth boundary.

Apx 26-38 cm, very dark grayish brown (10TR3/2) when moist silt loam; weak granular structure; few fine roots; many fine pores; gradual smooth boundary.

B_1 38-60 cm, dark brown (10YR3/3) when moist silt loam; moderate fine subangular blocky structure; few fine roots; common fine pores; gradual smooth boundary.

B_{21t} 60-90 cm, dark yellowish brown (10YR4/4) when moist silty clay loam; moderate medium prismatic structure.

B_{22t} 90-125 cm, dark yellowish brown (10YR4/4) when moist clay loam; moderate medium prismatic structure; few very fine pores; gradual smooth boundary.

B_{3t} 125-200 cm, dark yellowish brown (10YR4/6) when moist clay; moderate medium subangular blocky structure; clay skins abundant.

Bits of saprolite present in soil column at greater than 200 cm.

3. Site E4

A_p 0-26 cm, pale brown (10YR6/3) silt loam, very dark grayish brown (10YR3/2) when moist; moderate medium granular structure; abrupt smooth boundary.

B_1 26-46 cm, brown to dark brown (10YR4/3) when moist, silt loam; moderate medium subangular blocky structure; clear wavy boundary.

IIB_{2tb} 46-74 cm, brown to dark brown (10YR4/3) when moist, clay; weak medium prismatic structure; many mottles grayish brown (10YR5/2) and yellowish brown (10YR5/6); gradual wavy boundary.

$IICr_1$ 74-141 cm, yellowish brown (10YR5/6) when moist, clay; massive structure; few low and high chroma mottles; diffuse wavy boundary.

$IICr_2$ 141-150 cm, light olive gray (5Y6/2) when moist, clay; massive structure; many coarse yellowish brown (10YR5/6) mottles.