Soil Conditions Affecting Infiltration of Water and Root Development of Crop Plants

L. D. DONEEN AND D. W. HENDERSON[1]

Poor water penetration in California soils has become one of our major irrigation problems, and is considered by some authorities to be the foremost problem in plant-soil-water relations in our state. A water penetration problem at any given location may be caused by excessive adsorbed sodium, high clay content, or compaction. All these factors will be discussed, with emphasis on compaction by farm machinery.

It has long been realized that dense or heavy layers in the soil will prevent rapid percolation of water. As early as 1902 Mills (9)[2] described hard soil layers at the depth of plowing as "plowsoles" or "irrigation hardpans" which interfere with penetration of irrigation water in cultivated citrus groves. Since that time there has been considerable work on the problem, and it has been suggested that roots may not develop readily in these plowsoles. More recently Huberty (8) concluded that dense layers form most readily in soils with a wide range of particle sizes such as gravelly loams. Such investigations have been one of the contributing factors in the reduction of cultivation or working of the soil to a minimum, and many orchardists have adopted the practice of noncultivation.

With row crops such as sugar beets, considerable manipulation of the soil is necessary for preparation of the seed bed, weed control, furrowing for irrigation and harvesting. These operations should be kept at a minimum (5), but many of them must be performed under weather and soil moisture conditions not conducive to maintenance of good soil structure.[3] Recognizing that soil structure influences the rate of infiltration of water into soil, the Irrigation Division of the University has made preliminary investigations of some of the factors which influence physical properties of soil importance in water penetration and root development. These investigations have been carried out in several areas of the state, and have dealt with soils ranging in texture from very sandy soils to adobe clays and with many field crops, including sugar beets.

For purposes of discussion it is convenient to classify problem soils according to the cause of poor structure. It has been found that poor structure may be physical or chemical in origin, and that it may be present in soils in their natural state or may be produced by farming operations such as tillage and grazing. Poor structure is sometimes reflected in abnormally high apparent density, but there are problem soils whose densities are relatively low. Such soils have relatively high total porosity but a small percentage of large pores which apparently are important in rapid conduction of water (2) and root development. This phase of the problem is receiving further study.

Such a classification indicates that soil density is not a good criterion for studying soil structure, and this is true even for a given soil. This point is illustrated in Figure 1 in which infiltration rates of laboratory packed

[1] Associate Irrigation Agronomist and Junior Irrigationist, respectively, University of California, Davis, California.

[2] Numbers in parentheses refer to literature cited.

samples are plotted against density. At relatively low densities a small increase in density results in a large decrease in infiltration rate, while **at** high densities an increase in density results in only a slight decrease in the infiltration rate. Furthermore, the infiltration rate will differ widely in soils of different texture at the same density. Similar results have been reported by Bodman (4). However, density data have been included for soils in Tables 1, 2 and 3 to show how they fit into the classification used.

A specially designed sampler was developed for taking essentially undisturbed soil samples for laboratory determination of soil density and infiltration rates. The sampler utilizes paraffined cardboard cylindrical

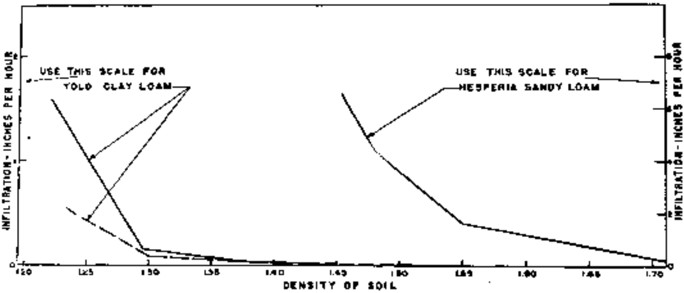

Figure 1. Effect of density of soil on the infiltration rate of irrigation water.

drug cartons $3^{1/2}$ inches in diameter and $7^{1/2}$ inches high for the inside liner and sample container. The full depth may be used or a sample can be sliced into any desired increments of depth (7).

Soils with poor structure are difficult to distinguish in the field, particularly if the soil is moist. When dry they are very hard and may be detected by an experienced observer. The authors at present conclude that making infiltration tests is the simplest way to detect compact layers occurring in normally friable soils. Such tests can be made either in the field or with undisturbed soil samples in the laboratory.

The present investigation is concerned not only with the infiltration of water into compact soils but also with the effects of poor soil structure on root development which is likewise very important in irrigation practice. The effects of poor soil structure on root development of sugar beets have been discussed by Baver and Farnsworth *(S)* and by Rietberg (12). Pendleton (11) compacted Chehalis and Willamette soils to a density of 1.95 gms./cc. and no beet roots penetrated them. At 1.8 the main taproot usually penerated the soil, but few feeder roots were formed.

[3] The term soil structure as used in this paper refers to pore size distribution rather than to shape of soil aggregates. A soil is considered to have good structure if it has an adequate percentage of large pores so that water and roots can penetrate readily.

High Density Soils

Soils of high density in their natural state have been reported by Veihmeyer and Hendrickson (13). They found densities of 1.8 to 1.9 in subsoils of the Bale series and some "primary chaparral" soils. Roots of several species of plants did not absorb water from these compact subsoils, and laboratory experiments with artificially packed soils indicated that plant roots were unable to penetrate the soil at that density. Similar experiments with other soils showed that sunflower roots would not enter sands at densities above 1.75, and the limiting density for root penetration varied from 1.46 to 1.63 for clay soils (14). Veihmeyer and Hendrickson concluded that soil density alone cannot be taken as the critical factor, and that the size of individual pores is probably important.

Hardpans or cemented layers would be placed in this category. Unless broken up they are considered impervious to water and roots. The authors believe that, except for hardpans, subsoils of high density are not commonly found in the alluvial soils of California.

Mechanically produced high soil density is a result of tillage operations and was first noted in California as plowsoles formed in citrus groves (9) and orchards from frequent tillage, usually with the moldboard plow. Old

Table 1.—Distribution of Soil Density with Depth.

Potato field[1]		**Cotton field[2]**		**Sudan grass field[3]**			
Depth	**Density**	**Depth**	**Density**	**Depth**	**Density**	**Depth**	**Density**
in.	gm/cc	in.	gm/cc	in.	gm/cc	in.	**gm/cc**
1-3	1.63	6-8	1.58	2-4	1.46	2-7	1.60
3-5	**1.74**	8-10	1.69	4-6	1.52	7-12	**1.70**
5-7	**1.70**	10-12	1.67	6-8	1.53	12-18	1.50
7-9	**1.67**	12-14	1.67	8-10	1.52	18-24	**1.37**
9-11	1.68	14-16	1.67	10-12	1.52		
11-13	1.66	16-18	1.61	12-14	1.50		

[1] Hesperia sandy loam—average of eight samples taken in bottom of furrow between potato rows. First inch discarded.

[2] Hesperia sandy loam—average of six samples taken between cotton rows. Surface six inches discarded because of loose condition of the soil from Cultivation.

[3] Yolo clay loam—in the left column average of eight samples taken at random from the field; columns on the right are for an average of four samples taken from the irrigation check having the lowest infiltration rate (0.1 inch per hour) of any in the field.

grainlands often have plowsoles and when the land is placed under irrigation these can be troublesome until they are broken up. The senior author has examined many of the grainland plowsoles when first converted from dryland production to irrigation of sugar beets. In these fields water ponded in local depressions or at the end of the furrows, and the sugar beets "drowned out." Examination showed that the plowsole prevented normal penetration of irrigation water with water frequently standing in the furrow for several days. The saturated soil above the plowsole caused an anaerobic condition, resulting in rotting of the root system and death of the plant. In some California areas the need for breaking up grainland plowsoles occurring at a depth of 5 to 7 inches below the soil surface is the principal cause of the general practice of plowing at least 12 inches deep for sugar beets (5) .

In recent years an overall study of water penetration problems has shown a general deterioration of soil structure. This condition is indicated in most cases by the compaction of soil from near the soil surface to a depth of 18 to 24 inches, rather than the relatively thin plowsoles described by most earlier investigators. Apparently the development of heavy farm machinery and tractors has contributed to the formation of the compacted surface layer in soils. This fact is illustrated by the data in Table 1. The soil of the potato field had a high density from 3 to 7 inches below the surface, and may be considered a plowsole. The samples were taken in furrows between 8-inch potato beds, and if the depths of the samples are referred to a leveled soil surface the densest layer would occur at about the 6- to 10-inch depth—a depth characteristic of plowsoles. However, the soil also had a relatively high density to depth of 13 inches (17 inches referred to the leveled soil surface). The soil from the cotton field was uniformly high in density to a depth of 16 inches. In the heavier soil of the Sudan grass field there was a uniformly high density to a depth of 14 inches. However, in a portion of the field with an extremely low rate of water penetration very high density occurred at the 7- to 12-inch depth, and the density was relatively high to a depth of about 18 to 24 inches.

In the summer of 1949 the authors' attention was called to several alfalfa fields in Kern County in which regularly spaced strips about one foot in width produced only small plants approximately 3 or 4 inches high, while plants in the areas between these strips grew to a normal height of about 20 inches. The soil densities in areas of poor and normal growth in two typical fields are given in Table 2. The soils in the poor strips were higher in density, especially in the 6- to 12-inch depth. These fields were merely disked after a crop of potatoes or cotton before being seeded to alfalfa, and it was evident that the dense strips were between the rows of the previous crop. The soil compaction resulted from cultivation, furrowing and harvesting operations.

Table 2.—Growth of Alfalfa and Soil Density[1]

Field	Alfalfa growth	Depth	Number samples	Density
	in.	in.		gm/cc
1	3	0-12	10	1.83
		12-24	4	1.72
		6-12	28	1.98
	18	0-12	10	1.68
		12-24	4	1.69
		6-12	30	1.69
2	3	6-12	28	1.88
	18	6-12	28	1.78

[1] Data obtained by J. D. Axtell, formerly Farm Adviser, Kern County, California.

Subsequently, many fields were visited where water penetration had become a problem. In all cases the grower reported that water penetration had formerly been adequate. Many of these fields are now irrigated three or four times as frequently as in the past, with the water held on the field much longer at each irrigation. The results of infiltration rates and soil densities determined on core samples from representative fields are reported in Table 3. The moisture equivalents (a laboratory estimation of field capacity) are given as a measure of the waterholding properties of the soils, and the footnotes list the soil type.

Samples 1 and 2 show difference in compaction by depth. A reduction of only 0.11 gms./cc. in density caused an increase in the infiltration rate of more than 200 percent. This soil is from the same potato field reported on in Table 1. Water stood in depressions and the ends of furrows for two or three days before soaking into the soil. Examination of the soil profile under the beds and furrows indicated that very few potato roots penetrated more than 2 or 3 inches below the bottom of the furrow. The soil density was 1.74 at this depth (see Table 1), and it is apparent that this soil was sufficiently compact to limit root development. The yield of this field was about half that of adjoining fields where compaction was not a problem, and there was an appreciably smaller percentage of U. S. No. 1 grade.

Samples 3 and 4 were taken from one side of the same field in an unplanted area where farm equipment was turned repeatedly in cultivating the field. The soil was of high density and low infiltration rate to a depth of at least 14 inches, apparently the result of farm machinery passing over the soil surface. An infiltration rate of 3 to 4 inches per hour is not unusual in these soils when they have good structure.

Samples 5 and 6 are also Hesperia sandy loam, but of a lighter phase as indicated by the moisture equivalent. Although the densities of this soil are as high as that of samples 1, 3 and 4, the infiltration rate averages 0.75 inch per hour, and excellent potatoes were produced in the field. These data emphasize the fact that soil density alone is not a sensitive criterion of the infiltration rate.

Samples 7 and 8 were obtained from an alfalfa field reported on in Table 2. The samples were taken during the third season after planting the crop. The alfalfa had not been killed out in the compacted strips, but the plants were still much smaller. These data are evidence that compaction in the strips is somewhat less than that at the time the crop was established At present the infiltration rates of these samples is nearly half that of the normally producing areas. These changes may be the result of many old root channels formed by young alfalfa plants which died out in the normal aging of the stand.

Samples 9 and 10 are from a barley field which received one irrigation when the crop was about half grown. This field strikingly showed the strips as described for the alfalfa field, but the strips were 18 to 20 inches wide, suggesting that the compacted strips were caused by a crawler type tractor. Sample 9 was taken from the compact area where water penetration had been so poor that barley plants were nearly dead from lack of water. Sample 10 was taken from an area of barley growing normally. Although the densities differed only slightly, the infiltration rate of the soil from the "normal" area is three and one-half times that of the compacted strips.

Poor water penetration in old irrigated pastures has been called to the attention of the authors. Since water penetration was no problem at the time these pastures were planted, the difficulty is apparently due to soil compaction caused by grazing when the soil is too wet. In some cases stock are left in the pasture during irrigation. Samples 11 and 12 were taken from one such pasture. Infiltration rates were measured by determining the rate of drop of the water surface in the cylinders. These cores simply did not transmit any water, and the apparent infiltration rate of 0.005 inch per hour can be accounted for by evaporation of water from the cylinders, since the bottoms of these samples remained relatively dry at the end of several days. The condition is so severe that water grass and other water-loving weeds crowd out pasture plants.

All of the above examples were taken from Kern County.

Samples 13 to 20 listed in Table 3 were taken in San Joaquin County and are examples of difficulties with heavier soil types. The samples were taken in tomato fields in the bottom of irrigation furrows, a level 5 or 6 inches below the ground surface before the beds were formed. Samples 13

Table 3.—Soil Densities and Rate of Water Infiltration on Undisturbed Soil Cores.

Sample number[1]	Depth sample	Number tests made	Infiltration	Soil density	Moisture equivalent
	in.		in./hr.	gm/cc	%
1	8-15	7	0.162	1.73	10.3
2	19-25	6	0.495	1.62	11.3
3	0-7	1	0.162	1.73	9.1
4	7-14	1	0.240	1.75	10.5
5	0-7	1	0.780	1.72	6.6
6	7-14	1	0.720	1.73	5.9
7	0-6	5	0.408	1.80	
8	5-12	3	0.875	1.75	
9	5-12	3	0.208	1.73	
10	5-12	3	0.764	1.71	
11	0-6		0.006	1.38	25.5
12	6-12		0.004	1.46	25.4
13	0-6		0.052	1.49	24.3
14	6-12		0.018	1.52	24.3
15	24-30		1.370	1.34	17.4
16	0-5		0.030	1.61	21.3
17	5-10		0.041	1.59	21.3
18	10-16		0.042	1.45	17.4
19	0-7		0.036	1.54	25.8
20	7-14		0.084	1.49	25.8
21	2-7	4	0.031	1.60	21.0
22	7-12	4	0.012	1.70	22.2
23	12-18	4	0.017	1.50	26.4
24	18-24	4	0.660	1.37	27.1

[1] Nos. 1 and 2. Hesperia sandy loam. Core samples taken the spring following potatoes after the soil was plowed but before planting cotton.

Nos. 3 and 4. Hesperia sandy loam. Adjacent to field where samples 1 and 2 were collected. An area between power poles cultivated only for weed control.

Nos. 5 and 6. Hesperia sandy loam. Cores taken from bottom of furrow in a potato field.

Nos. 7 and 8. Exeter sandy loam. 7, small alfalfa plants from tractor compaction; 8, samples about 15 inches from No. 7 where large alfalfa plants were growing vigorously.

Nos. 9 and 10. Delano loamy soil. 9, in barley field where strips showed deficiency of soil moisture; 10, about 2 feet from sample 9 where barley was normal and showing no water deficiency.

Nos. 11 and 12. Cajon clay loam. An old irrigated pasture.

Nos. 13, 14 and 15. Rincon clay. Core samples taken from bottom of irrigation furrow in a field of tomatoes.

Nos. 16, 17 and 18. Sorrento silty clay. Core samples taken from the bottom of the irrigation furrow in a field of tomatoes.

Nos. 19 and 20. Stockton clay adobe. Samples taken from the bottom of an irrigation furrow in a field of tomatoes.

Nos. 21, 22, 23 and 24. Yolo clay loam. Samples taken from a Sudan grass field.

and 14 were taken from the first food of a dense layer of Rincon clay extending to a depth of about 22 inches. Sample Sample 15 was secured from the friable soil below this depth. The friable soil had an infiltration rate seven and one-half times that of the compacted layer. Samples 16, 17 and

18 are from a soil classified as Sorrento silty clay which has a dense layer at least 16 inches in depth with a very low infiltration rate. Probing and digging indicated that the layer was approximately 22 inches thick. Samples 19 and 20 were taken in a Stockton clay adobe. The soil is very dense, considering its heavy texture, and the infiltration rate is very low. Below the 24-inch depth there was an extremely heavy clay (moisture equivalent = 39) with a density of 1.68. Apparently this soil is similar to the dense subsoils reported by Veihmeyer and Hendrickson (13).

Excavations were made in all the tomato fields and the roots were examined. A heavy mass of both large and small roots was found in the surface 8- to 10-inch depth which included the cultivated layer plus the soil from the furrows. Only a few slender roots penetrated the dense layers. There was no branching in the compact zone, but there was considerable branching in the more friable soil below.

Samples 21, 22, 23 and 24 were taken from a field of the University Farm at Davis, and indicate compaction to a depth of 18 inches with a resulting low infiltration rate. Sample 24, taken from below the 18-inch depth, is only slightly more dense than is normal for this soil.

These examples are from only a few of many investigated during the past two years. Although Table 3 reports only on light and heavy soils, dense layers have been found in loam soils as well. The condition does not predominate in any soil textural class.

Additional studies on root development in compact Yolo soil listed as sample 21 in Table 3 were made with 60 core samples 4 inches in depth. Two inches of loose sieved soil from the same location were placed on top of these cores.

They were divided into groups of 12 with each group planted to one of the following crops: Beans, tomatoes, onions, sunflowers and wheat. After the plants had reached a size large enough to have a well developed root system, the containers were removed and root systems in the dense soil studied. It was found that none of the crops had any appreciable number of roots in the compact soil, with the exception of wheat, which had approximately 25 percent of the total root system by weight growing in the compact layer. Wheat roots have a smaller diameter than any of the other plants studied. The occasional roots of plants other than wheat found in the dense layer usually followed an old root channel, and sometimes grew through the partly decomposed old root. Figure 2 illustrates the root development of beans. The roots grew between the container and the dense soil. They were flattened so that they were four to five times as wide as they were thick. All branching of the roots was parallel to the surface of the dense soil on the sides as well as on the bottom of the container.

No quick and easy solution has been found for the problems arising from compacted soils caused by farm operations. The most intelligent approach seems to be prevention of compaction as much as prossible by careful soil management. In this connection, the moisture content at which a soil is worked is popularly believed to be important. A study of the effect of the passage of a wheel tractor over Hesperia sandy loam at various soil moisture content has been made, using the infiltration rate of the soil as a criterion of compaction. The results of this experiment are to be published in detail elsewhere (7) . The authors concluded, however, that the drier the soil the smaller the decrease in infiltration rate, although there was a significant decrease even when the surface 6 inches of soil was below the wilting percentage.

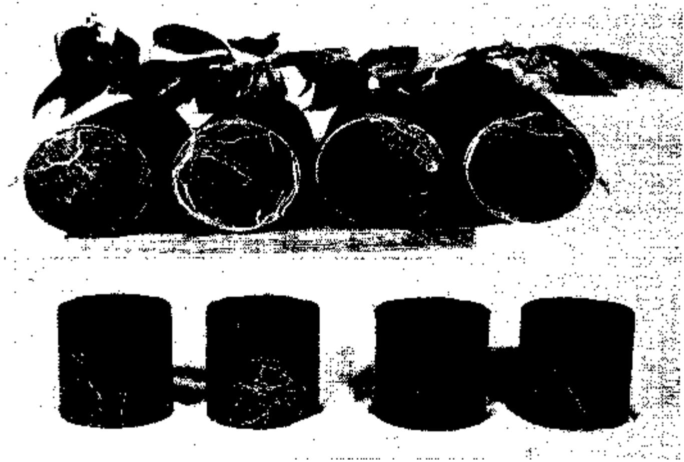

Figure 2. Root development of beans in undisturbed soil samples from a field having a soil density of 1.60.

Soils with low volume weight

Low volume weight soils naturally occurring under certain conditions may have extremely poor structure preventing normal root development and limiting water penetration. Such a soil, classed as Tulare clay, occurs in the lower part of the Tulare lake basin. The area has been extensively farmed to winter barley, and summer crops are failures. Investigation in this area, where cotton was growing, indicated the roots were limited to the cultivated soil. Below this friable surface layer was a tight, plastic clay about 20 inches in depth which rested on loam soil. The density of the soil from this tight clay layer is about 1.1 to 1.2, which is considered low. The clay content averages about 70 percent, with most of the remaining percentage as silt. The moisture equivalent averages about 50 percent. There is no essential difference between the cultivated layer and the tight subsoil in clay and silt content or moisture equivalent. During the summer most of the taproots of the cotton plant will slowly penetrate through this dense layer, and once through they send out many branch roots. These cotton plants are so stunted they rarely reach a height of more than 10 to 15 inches, and bolls are set so late in the summer they do not mature. In about the third or fourth year of summer cropping normal cotton will be produced, or if the soil is broken up and allowed to dry as in old irrigation ditches, normal plants are produced the first year. There is a great deal of shrinking on drying and a soil of crumb structure is formed which water and roots can penetrate.

These tight soils are in the bottom part of the lake bed where the fine materials from the river waters settled out. Apparently no large pores were formed. All the tight subsoils need is a few cycles of wetting and drying and an improved soil structure will result. The authors believe similar conditions exist in some of the ricelands of the Sacramento Valley. Some claypans are also of low density but nearly impervious to roots and transmit water slowly.

Sodium-dispersed soils usually have a low density. As the sodium content of the soil increases there is a tendency toward dispersion of the colloidal fraction of the soil, destroying structure and eliminating large voids or pores. When this condition is reached, the soil becomes quite impermeable to water. This situation occurs in the sodium saline and alkali soils. Such soils are usually obvious to investigators in the field, either from the salt accumulation on the soil surface or a dark or black discoloration from the sodium alkali—"black alkali." If excessive sodium is suspected, simple field or laboratory tests can be made. Some of the sodium-dispersed soils caused by the use of an irrigation water containing a high percentage of sodium salt are not so easily detectable. Doneen (6) and Axtell and Doneen (1) have reported a deterioration of soil structure and a greatly reduced permeability of the soil from the use of these high sodium waters. There are no obvious symptoms in the field to distinguish this cause of low infiltration rates from some of the others discussed above, and at present there are no simple laboratory tests. The simplest method, without involving a great deal of laboratory analysis, is to make an infiltration test with a high calcium water. The present method used by the authors is to make an infiltration test with a water containing 10 to 20 milligram equivalents per liter (860 to 1,720 parts per million) of gypsum (calcium sulfate). If the infiltration rate increases as the gypsum water penetrates the soil, it is usually sodium-dispersed.

Upon drying, sodium-dispersed soils are hard and are difficult to distinguish from the compacted soils mentioned above. A sodium-dispersed clay soil has a tendency to crack on drying, but with the compact soil little shrinkage takes place. In the sandy soil where little cracking is in evidence, it is very difficult to distinguish between sodium-dispersed and compacted soil. The effect of sodium-dispersed soils on root development has not been fully investigated, but observations have indicated that most plants will develop roots under this condition.

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