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Aeration, Compaction, and Drainage

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Aeration, compaction and drainage – each is a broad and complex subject. In order to narrow the scope of this discussion, emphasis will be placed upon aeration while compaction and drainage will be discussed as they are related to aeration.

As a root undergoes respiration, oxygen is consumed and carbon dioxide is released. Aeration is the process of gaseous transfer between the aerial atmosphere and the root zone. Diffusion is the most important factor in gaseous exchange between the air and soil. As is illustrated in figure 1, oxygen diffuses through the air filled pores of the soil, dissolves in water and diffuses through the water to the root. The relative rate of diffusion in air and water might be likened to a flight in a jet liner in air and swimming in water, although actual diffusion rates are much slower. Carbon dioxide follows the same general process in the opposite direction. Since diffusion of oxygen is important it is well to consider the factors which influence the diffusion rate.

Air Space and Water Film

It has been found that the diffusion rate through the pore spaces is directly proportional to the fraction of the soil which is air. Or, in other words, the greater amount of air space in the soil, the faster the diffusion will be. The effects of compaction and drainage upon aeration are readily seen on their effects on the air space as illustrated in figure 2. Part A represents a

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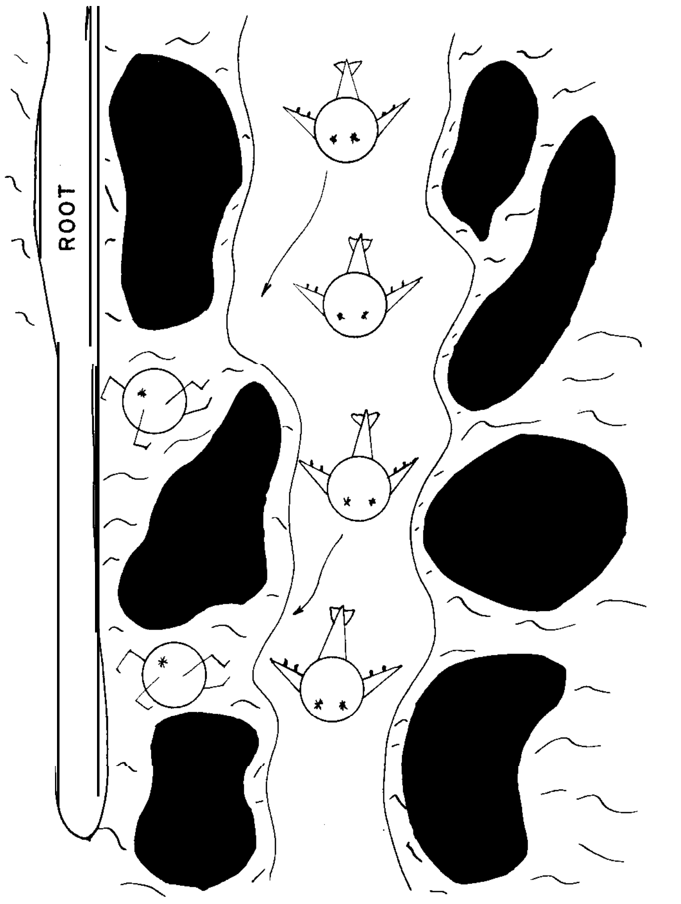

FIG. 1 – SCHEMATIC DRAWING OF OXYGEN MOVEMENT THROUGH AIR SPACE AND LIQUID FILM TO ROOT SURFACE.

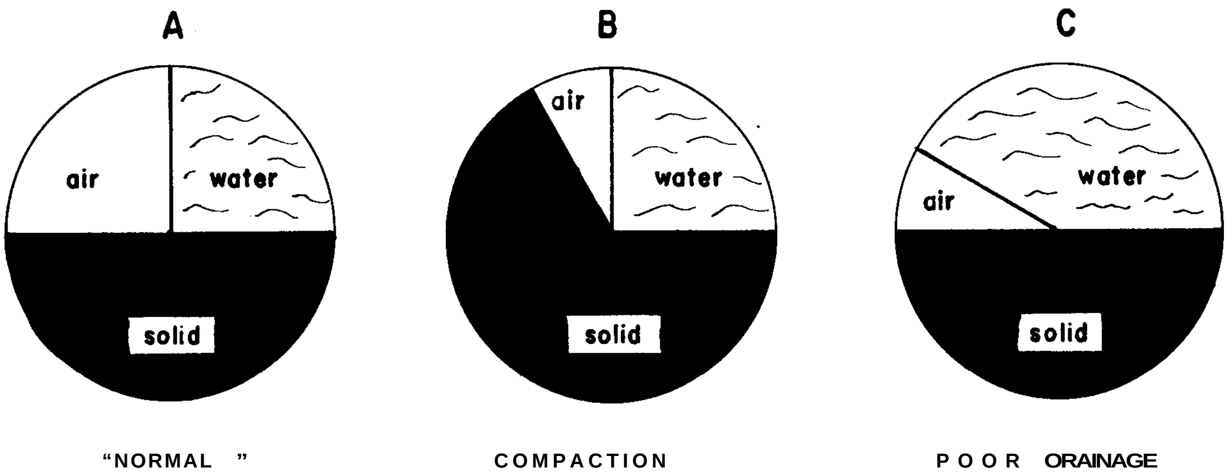

FIG. 2 – THE EFFECT OF COMPACTION AND POOR DRAINAGE ON VOLUME OF AIR SPACE.

"normal" soil where one-half the volume is solid and one-fourth each water and air. If the "normal" soil becomes compacted, a situation like Part B will exist and the air space is reduced. Part C represents poor drainage and again the air space is reduced. Therefore compaction and poor drainage will decrease the rate of diffusion through the soil pores.

As previously stated, oxygen must dissolve in the water and diffuse through the water to the root surface before it becomes available for plant use. The travel of oxygen through water is extremely slow so the thickness of water film surrounding the root is very important. Again the importance of drainage can be seen. Poor drainage impedes aeration by decreasing the air space and by causing a larger film of water through which the oxygen must pass to the root.

How important is Aeration

We have learned that oxygen diffuses to and carbon dioxide from the root and that the rate of movement is determined by the air space and film thickness. The question might now be asked, "so what?" What does all this mean in terms of plant growth?

Cooperative work between Dr. L. H. Stolzy of UCR and Dr. 0. R. Lunt and Dr. J. Letey of UCLA has been and is being done on studying soil aetation and plant growth. The results which will be presented here are for snapdragons. Studies on turfgrass are presently under way but results are incomplete. The general results found for snapdragons will probably apply to turfgrass as well.

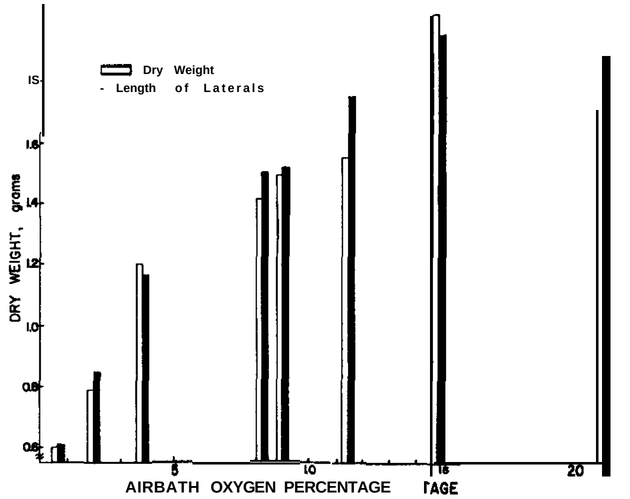

FIG. 4 -SHOOT GROWTH OF SNAPDRAGONS AT VARIOUS OXYGEN LEVELS

Oxygen has a very marked effect on root growth. A photograph showing the root growth of plants grown with different amounts of oxygen at the soil surface is presented in figure 3. Both the depth of penetration and vigor of the roots can be seen to be influenced by oxygen. The roots which are visible for the < 1% oxygen treatment are those which were present before the treatments were applied. No further root growth was noted in that particular treatment. A good root system is necessary for a strong healthy plant. The plant feeding zone for both water and nutrients is determined by the extent of the root system. On hot dry days, plants with a very poor root system can actually wilt even though soil moisture would appear not to be limiting. Root growth then is one phase of the plant activity which requires adequate oxygen.

Figure 4 shows the effect of oxygen on shoot growth.

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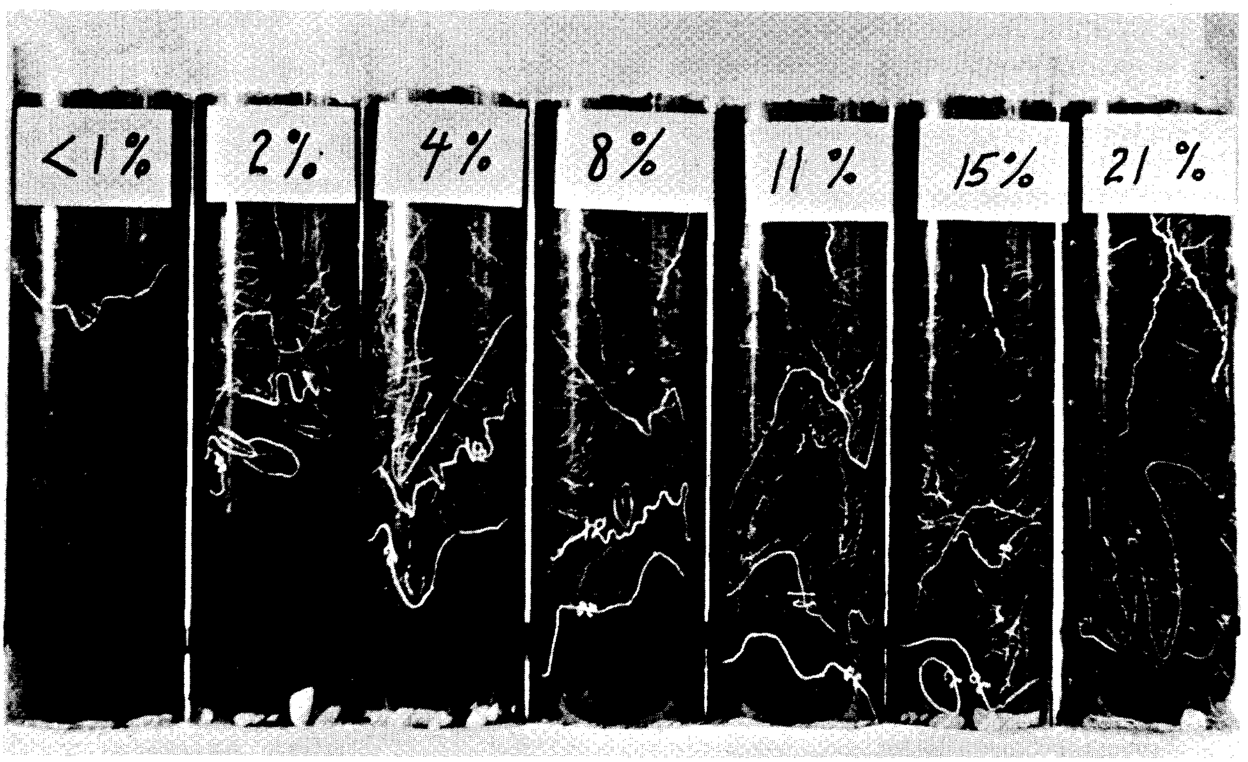

FIG. 3 - ROOT GROWTH OF SNAPDRAGONS AT VARIOUS OXYGEN LEVELS

Again it can be observed that in general as oxygen increases, shoot growth increases.

Analysis of the shoot for various minerals produced more information on the necessity for oxygen, and those data are presented in figure 5. Increased oxygen enhanced K and P uptake. The total Ca + Mg (these were not analyzed individually) does not appear to be greatly influenced by oxygen. In contrast to the other minerals, Na increases with decreasing oxygen and is very markedly higher at the lowest oxygen treatment. This observation hints that poor aeration could cause an apparent sodium problem even though the soil is not particularly high in sodium. Oxygen supply is therefore important with respect to plant nutrition.

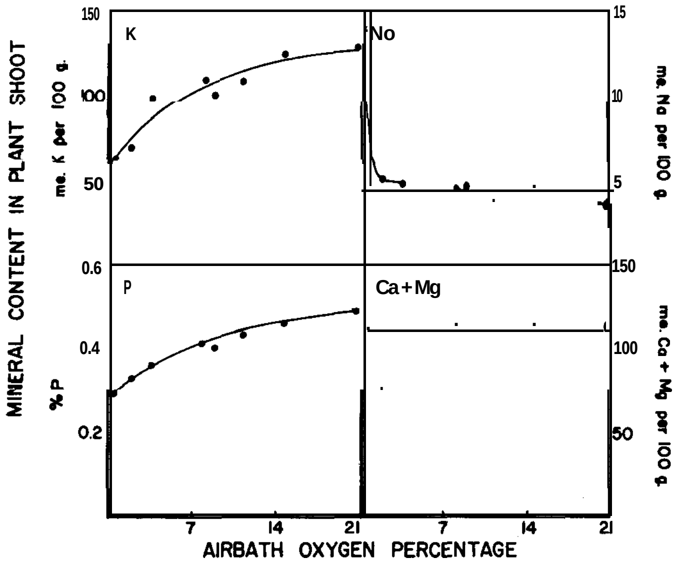

FIG. 5 - CONCENTRATION OF VARIOUS MINERALS IN SNAPDRAGON SHOOTS GROWN AT VARIOUS OXYGEN LEVELS

Although no data will be presented, it has been found that plant resistance to pathogens is influenced by the soil aeration. While other factors could be pointed out, enough evidence has been presented to show that soil aeration is very important in many phases of plant growth. Just as we are careful to provide adequate nutrients to a plant, we should strive toward conditions where soil aeration will not become limiting.

How is Aeration Measured?

Granted now that aeration is important, how can we know if we have a poor aeration condition? The statement, "poor growth was due to poor aeration", has often been made although no measurements were made on aeration. The development of reliable methods of measuring soil aeration has lagged behind other phases of scientific research in this field. Extraction of gaseous samples from the soil pores for analysis have in general not been entirely satisfactory because of the difficulty in extracting samples from the smallest air spaces without sucking in gas from the aerial atmosphere. Furthermore, the concentration of oxygen in the pore space is not the entire answer because it must still diffuse through the water to the root surface.

The rather recent development of the platinum microelectrode technique for measurement of oxygen diffusion rates in soils shows promise toward plugging this large gap in soil aeration investigation. It is impossible to go into all of the details involved in making oxygen diffusion rates, but a brief description of the principle involved can be presented. A platinum wire electrode which represents a root is placed in the soil. A calomel half cell with salt bridge is used as the other electrode. Under specific conditions, the current which flows between the electrodes is dependent on the rate of oxygen diffusion to the platinum wire which represents the root. The oxygen diffusion rate can therefore be calculated from the electric current.

Measurement of the oxygen diffusion rate is only part of the solution. One must know how to interpret the diffusion rates with respect to plant growth. Research being done at the University of California, Los Angeles and Riverside, is providing some correlation between oxygen diffusion rates and plant response. Although the work is by no means complete, it appears that roots will not grow into an area where the oxygen diffusion rate is less that 20 x 10^{-8} gm cm^{-2} $min.^{-1}$. The range between 20 and 30 is very critical and rates above 50 or 60 (all times 10^{-8} gm cm^{-2} min^{-1} are probably sufficient to maintain maximum growth. These values may be modified somewhat by continued research. The time is near at hand when we will no longer have to guess on the aeration status of a soil.

Table 1 shows the results of diffusion measurements made by Dr. Stolzy on putting greens. Characteristic of the results is the poor aeration condition which was found. The area that looked good was the only one where diffusion rate was optimum at the very shallow depth of 2 inches. The good area would not have optimum root growth at 4 inches. All other areas and depths tested indicated that roots should not grow. Obviously since grass is there, roots must have at sometime made some growth. The results reported are for the time that measurements were made and possibly the rates would have been better at some other time, but they do indicate that aeration is not always optimum and in fact very poor at times.

TABLE 1

Oxygen diffusion rates measured on putting greens.

Green Appearance	Depth(inches)	X10^8g cm^{-2} min^{-1}
Good	2	51.6
	4	27.1
	12	3.8
Bad	2	10.0
	4	10.2
Good, but getting worse	2	13.6
	4	14.7
	8	7.5
	12	4.1

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What Can Be Done

The improvement of a poor aeration condition is different than some of the other problems. If water is limiting for plant growth, it is alleviated by applications of water. If soil nutrients are low, nutrients are added. When soil aeration is poor, a direct application of oxygen is not feasible. Soil aeration has to be attacked by indirect means. Anything which will promote higher oxygen diffusion rates can be considered to be an improvement in soil aeration. Drainage and compaction have been discussed as they influence aeration. The promotion of good drainage and low compaction will improve aeration. Since they are important, each will be briefly discussed later.

It has become a common practice to "aerate" turf. Machines of various designs are pushed or run across the turf which pull out small cores of soil leaving the turf with a network of holes. Theoretically this process should improve aeration because atmospheric air can get into the holes and a three dimensional diffusion rather than predominantly one dimensional diffusion can occur. Furthermore the distance that oxygen must diffuse is shortened. The term "theoretically" was used because, to the author's knowledge, no actual measurements have been made to indicate that such is the case. Again actual physical measurements have fallen behind the assumptions which are made from preconceived ideas. The mechanical "aeration" of soil probably improves infiltration and possibly drainage which again would possibly aid aeration. These words are not written with the intention of casting doubt on the usefulness of soil "aeration", but merely to indicate that physical measurements to support such are lacking.

Compaction

As was previously stated, compaction is a broad subject and will by no means be completely covered. The direct effect of compaction on aeration whereby the air, space of a soil is reduced has been pointed out. Compaction has other indirect relationships to aeration. A compacted soil may not allow water to penetrate, causing water to remain on the soil surface. This would create a very poor aeration condition. Furthermore, a compacted soil will retain more water than a less compacted one.

Closely associated with compaction is the aggregation and aggregate stability of the soil. A well aggregated soil is less susceptible to compaction than a dispersed soil. The effects of compaction on a well aggregated soil are less severe than on a dispersed soil because of the presence of larger pore spaces which allow faster water intake and better drainage.

The most important factor in the compaction of soils is the traffic which passes over. Figure 6 illustrates how traffic can compact soil, thus decreasing infiltration rates. Infiltration measurements were taken at five loca-

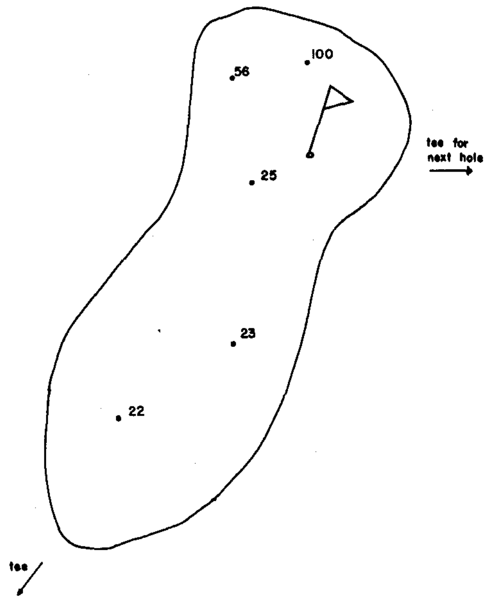

FIG. 6 – RELATIVE INFILTRATION RATES AT VARIOUS POSITIONS ON A PUTTING GREEN

tions on a putting green. The numbers represent relative infiltration rates with 100 being the fastest. The lowest infiltration rates are found on the green between the hole and tee. It is very probable that most golfers would walk across this portion of the green almost regardless of where the ball landed. Only those who hit the ball beyond the hole would walk on that part of the green and thus there is the probability of less traffic beyond the hole where infiltration rates were found to be higher.

The moisture content of the soil when traffic is applied is very important in the extent of compaction which will occur. Figure 7 presents curves to indicate how moisture will affect resistance to compaction.

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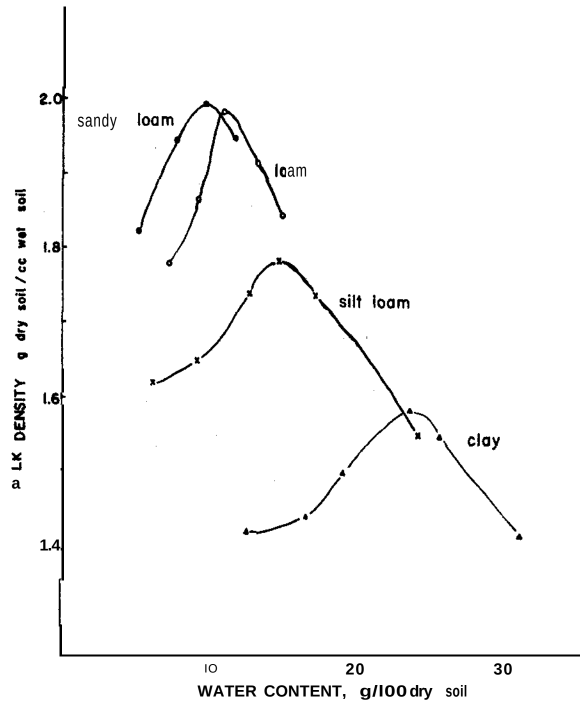

FIG. 7 - COMPACTION - MOISTURE CONTENT CURVES FOR SOILS OF VARIOUS TEXTURES

Drainage

There are two aspects of drainage to consider. First, surface drainage must be such that no low spots exist wherein water would be trapped and become ponded. This is usually a minor problem. Usually a greater problem is the internal drainage of water from the soil so that it will not remain saturated and thus hinder aeration. Some soil profiles have natural drainage whereby the water can rather freely percolate to deeper layers and be removed by lateral flow. Often, for various reasons, rather impervious layers exist which do not permit the rapid passage of water. When conditions exist where water is not removed fast enough or deep enough, artificial drainage systems must be installed. A tile line is installed to convey water out of a given area into a drainage ditch. However, before a tile line is effective, water must flow into it. The rate of water flow into the tile is dependent upon the permeability of the soil. Here again is an interrelationship between drainage and compaction and aggregation as high compaction and/or poor aggregation decreases the permeability of the soil. The depth and position of tile also influence the rate of drainage. In general, the soil is drained faster when the tile is placed deeper and with closer spacing between laterals.

In southern California, it is important to remember that some drainage must occur either from natural or artificial means or salts will accumulate in the soil. Drainage must occur to periodically wash the salts from the root zone. If natural deep percolation is slow, an artificial drainage system should be installed. Needless to say, irrigation practices will have a great influence on the requirements of a drainage system.

In conclusion – the soil physical properties are vitally important in plant growth. The soil physical properties are quite often interrelated, wherein the modification of one will cause the modification of others. Good controlled examination by soil physicists of soil physical properties in relation to turfgrass management are meager which makes it necessary to translate the results of studies conducted under different conditions to what might be expected in turfgrass. Most often this is adequate; occasionally it may be futile.

Water Management of Turfgrasses and Trees

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Irrigation is one of the most important practices under the control of the turfgrass manager in the maintenance of a healthy and attractive grassed area. Turfgrasses probably are injured as often by improper irrigation as by failure to irrigate soon enough.

Why is proper lawn irrigation so important? By using careful irrigation practices, considerable water, watering time, and labor costs can often be saved. As an example, if you are running your irrigation on 45-minute sets and find 40 minutes will do, this is one ninth or 12 1/2 per cent saved. Look at your total water expense – perhaps money saved on this small difference can purchase some much needed equipment or may permit salary increases.

If "thatch" or a surface compaction layer decreases water infiltration so that shallow rooting develops, frequent irrigation is a must. In recent trials, after 45 minutes of watering, in 5 out of 6 places tested, the water had not infiltrated through the thatch. These same results were shown at other locations. Removing the thatch by verti-cutting or by renovation, and overcoming surface compaction with an aerification program, will achieve deeper rooting. This will result in better water infiltration, using less water. Irrigation frequencies can then be lengthened, resulting in a savings in labor and water costs. This savings in most cases will more than pay for the expense of the thatch removal and aerification to overcome compaction.

Overirrigation on well-drained soils leaches out available nutrients beyond the root zone of the plants, thereby increasing the need for fertilizing more often. Symptoms of nitrogen deficiency are common on overwatered turf.

Most important of all will be the improved appearance and health of the turfgrass. A vigorous turfgrass is better able to withstand attacks of insects and diseases and to crowd out weeds. It can better stand up under wear and adverse conditions.

Irrigation needs of plants vary, as do the rooting depths of lawns, shrubs and trees. How deep do grass roots grow? Grasses will develop surprisingly deep roots if given an opportunity. The various species have different rooting capabilities. Under favorable soil and moisture conditions, bents, red fescues and dichondra may have active root zones to a depth of one foot; blue grasses, 2.5 feet; tall fescues, 3.5 feet; and Bermuda grasses, more than 4 feet. Even under very young stands only a few months old roots may extend to a depth of a foot or more. Trees may have an active root zone from three to five feet deep.

Most lawns have shallow roots, usually located in the top four to six inches of soil. Where shallow rooting occurs it is usually the direct result of unfavorable soil conditions or poor management practices. Clay pans or

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hard pans within a foot below the surface interfere with maximum root development. Other common causes of shallow roots are the subsoil being kept too wet by excessive irrigation or too dry by light irrigations.

A practical water program embodies three basic concepts. Each concept may be set forth as a question: (1) How should water be applied? (2) How much water should be applied? (3) How often should water be applied?

Manner of Applying Water

Water should be applied at a rate no faster than it can be absorbed by the soil. The nature of the soil and the slope will dictate the rate water may be applied.

Surface runoff of water is wasteful. When runoff occurs, the normal impulse is to turn off the sprinklers in the belief that the soil has been wet to an adequate depth. Actually, only a shallow layer of soil may have been wet. If runoff occurs before sufficient water has been applied to wet to the desired depth, shut off the water for at least one or two hours and then complete the irrigation.

When runoff starts early it is because sprinklers apply water faster than the soil can absorb it. The sprinkler system should then be modified to reduce the rate of water application. Heads are available for low application rates. A soaker which applies water at a very slow rate can often be used to advantage on problem areas. Where runoff can be avoided, water infiltration is better and high and low areas will be more uniform.

The time of day selected for watering may influence both irrigation efficiency and condition of the grass. An ideal time to water is near sunrise. Highest irrigation efficiency can be attained when the temperature is low, humidity high, and wind absent. The most uniform distribution of water can be expected when water pressure is ample and there is no wind to distort the sprinkler pattern.

Watering lawns in full sunlight during the heat of the day seldom harms grass. Watering is less desirable at this time, if the temperature is high, humidity low or the wind strong. Water pressure is often low during the late afternoon and early evening; this reduces the ability of a sprinkler system to operate satisfactorily and give the coverage of which it is capable.

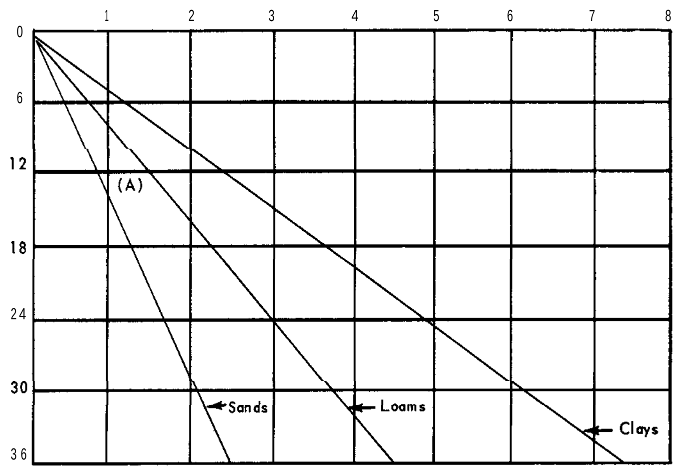
Lawns watered in late afternoon or early evening remain damp all night – an encouragement to diseases if nights are warm. Watering early in the day permits the grass to dry rapidly and may reduce the likelihood of disease problems occurring.

Amount of Water to Apply

The amount of water to apply at any one time will depend upon the water-holding capacity of the soil, the amount of moisture present when irrigation is started, drainage, the active root zone of the plant, and the possible root zone. Loams and clay loams are generally considered to have desirable water-holding capacity, whereas sands display very little water-retention values. The following chart, prepared by Dr. Robert M. Hagan of the University of California, Davis, will aid in determining how much water must be applied to soak into typical soils to wet to a given depth.

CHART NO. 1

Surface Inches of Water Required to Wet Soils to Given Depths, assuming No Surface Runoff



HOW TO READ CHART: Figures at top denote depth of water required in inches. Figures at left denote depth of soil to be wet in inches. If a 12-inch depth of loam soil is to be wet, run down left-hand scale to 12-inch line, then across chart to diagonal line labeled "Loam" (at point A). Then project line vertically up to scale across top of chart. Depth of water required is 1 1/2 inches.

Once the soil has been wet throughout the root zones, or after contact with subsoil moisture has occurred, any additional water applied will be excess. The drier the soil at the time of irrigation, the more water and time are required to wet to a given depth. Everywhere that water penetration is a poblem, soils should be wet to the full depth of rooting early in the season to insure good water penetration throughout the summer.

Removal of excess water from the soils is referred to as drainage. Unless soils are adequately drained, many problems arise because of the slow removal of excess water. Aeration is limited and often a soggy subsoil is created which may kill the deeper roots of the grass and of nearby trees or shrubs. Overirrigation must be avoided where drainage is limited.

The amount of water to apply each time should be determined by the needs of the areas in the soil where the majority of the active roots are located and where only a few roots are found and into which it is practical and possible to extend the root zone.

Roots will not grow into a dry soil nor will they seek

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out moisture. Neither will they grow into a soil that is too wet. Therefore, it will be advantageous to alternate the length of irrigation sets so that only enough water is applied to wet the upper active root zone of the plants until the lower zone, where fewer roots are found and water extraction is less, has dried to some extent. Then, enough water can be applied to wet the lower root zone. On a sandy soil this program may not be as important as on the denser clay soils. It is very important to remember that about two or three times a year the soils should be wet sufficiently to flush the mineral salts below the root zones of the plants.

In determining how much water to apply it is essential to water the trees, which have a deeper root zone, according to their needs and not rely on the water program for the turfgrass to satisfy the requirements of the trees.

Frequency of Irrigation

No single answer can be given. This depends upon the type of grass and the area in the soil where most of the roots are located, the soil type, and the supply of available moisture within the root zone, and climatic conditions, such as rainfall, humidity, temperature, and wind. Perhaps one of the most important factors contributing to improper watering is frequent irrigation – watering too often. Frequent, shallow watering tends to keep the upper layers of soil near a point of saturation most of the time. Although this may supply enough moisture to the lawn to keep it looking good for a time, it encourages shallow rooting and promotes weak turf susceptible to weeds, diseases, and insect attack, as well as damage from traffic. Many of our turf areas are watered too frequently and for too short a time.

Grasses for healthy growth and a satisfactory appearance need a constant supply of available moisture but water should be applied only when necessary. In general, it is an excellent idea to let the condition of the grass determine when to apply moisture. A healthy, well-fertilized lawn can show the first appearance of wilting with little or no detriment to its growth. This is not so with a **weak,** nitrogen-deficient lawn. Shrubs and trees do not show visible symptoms of wilting until some permanent damage has been sustained; therefore, they should be irrigated before wilting appears.

Very often, the frequency of irrigation is determined by the appearance of a few dry areas which only constitute perhaps 10 per cent of the total area. How much better it would be to water the 90 per cent of good area according to its needs and come back and correct the problems causing the drier locations to receive or absorb less water.

In a situation where the grass transpires faster than the roots can absorb water, “syringing” or “showering” is needed. Water applied as a fine mist will cool the turf and prevent wilting. The object is to apply some moisture to the turf but not to the soil which may be wet enough already.

Conclusion

Any changes in irrigation schedules should be gradual, not attempted all at one time. This is especially important if, due to previous light sprinklings or unfavorable subsoil conditions, shallow rooting has developed.

How deeply to water and how frequently to water can be determined by the following program: Water to a depth where the majority of the roots of the plants are located (usually from 4 to 6 inches with grasses and 2 to 3 feet for trees) as often as the plants indicate they require additional moisture. Water to the depth where only a few roots are or to which it is possible to develop the root system (grasses usually 12 to 18 inches and trees 3 to 5 feet), when the soil begins to dry out at these lower depths. Gradually the irrigation frequency can then be lengthened with a longer watering time as roots develop to a deeper depth. Use good judgment.

Trials are now being conducted with shade trees and turfgrass, using tensiometers, to determine the frequency and length of irrigation. It is sincerely believed that there is a means at least of accurately determining how much and how often to irrigate.

Acknowledgment –– Acknowledgment is gratefully made for information taken from an article by Dr. Robert M. Hagan, Department of Irrigation, University of California, Davis, California.

Soil Mixes and Turfgrass Management

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In managing turfgrass, the importance of the selection of the proper variety, cutting height and disease and pest control can hardly be overemphasized. Our particular concern today, however, is soil and water management. The soil must supply water and minerals to the root and permit the free exchange of gases to and from the root. The turfgrass operator should have at his disposal control over the frequency and amount of water to apply. As I will point out later, major improvements or simplifications are in sight for the control of fertility. One of the principal soil management problems the turfman has to deal with is the maintenance of adequate infiltration rates. The importance of good permeability as related to irrigation, and salinity has already been alluded to. Permeable soils are easily irrigated properly, and salinity problems are easily controlled. Furthermore, permeable soils are usually well aerated unless the water table is close to the surface.

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Infiltration rates are often very poor in turf areas due to the fact that they are used so much, and traffic often comes when the moisture content is conducive to compaction. Infiltration rates in heavily used turfed areas were measured in a number of locations several years ago by Marston Kimball and myself and found to frequently fall below 0.1 inch per hour. One of the most prevalent problems in turfgrass management is the poor infiltration rate. We strongly recommend regular cultivation (aerification) of heavily used areas to maintain infiltration rates and to overcome compaction.

A second management aid where new installations are being made is to permit the grass to become well established before subjecting it to heavy use. The grass and its thatch protects the soil surface.

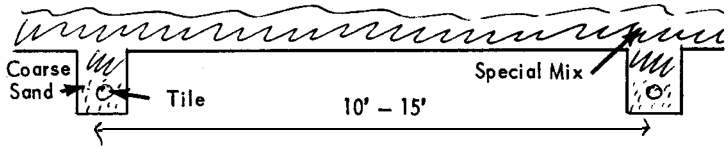
In considering soil and turfgrass management problems, it is convenient to classify the turfgrass on the basis of several use classes:

1. General purpose
   a. Lawns b. Parks c. Cemetery
2. Sports fields for running games.
   a. Football b. Baseball
3. Sports fields for non-running games.
   a. Golf greens b. Bowling greens

The use of special soil mixes is warranted for high value, demanding turfgrass areas such as the bowling and putting green. We have recommended the use of special sand mixes for these purposes. Such mixes are not feasible on sport fields where running games are played because the low cohesion of the soil makes slippage too prevalent. While we are still involved in work to refine our recommendations for soil mixes for putting greens, the following specifications for the sand to be used in the mix have given good results:

50 percent or more should be smaller than 0.4 mm dia.
25 percent or more should be smaller than 0.25 mm.
Less than 10 percent should be smaller than 0.10 mm.

If sand of these specifications is blended with about 20 to 25 percent by volume of redwood sawdust or coarse peat, a mix is obtained which has good resiliency and retains sufficient water when used in relatively shallow depths. The organic matter need only be blended into the top 4 or 5 inches of the green. Soil mixes of this type have been shown to remain highly permeable in spite of the compactive treatment they may receive. If the soil under the green has poor permeability then the use of tile drainage is required. Typical spacing on the tile is 10 to 15 feet apart. The tile should be at least 24 inches deep and there should be no interface between the soil surface and a depth of 20 inches which will impede water movement. Ideally, the soil mix would be 20 to 24 inches deep over the entire green, however, in order to reduce costs, some greenskeepers have used about a 12 inch depth and obtained the extra 8 to 12 inches of profile depth by placing the tile in trenches sufficiently deep to achieve the desired depth of the profile as shown in the diagram:



The adequacy of drainage in the sand layer between the tile needs to be evaluated. It seems probable to the author that this area would normally be expected to drain sufficiently if the sand meets the specifications indicated.

A major problem in managing the special sandy mix greens has been the maintenance of fertility since the sand and organic matter has little retentive capacity for a number of the elements required by plants. New developments are in sight in the way of long lasting fertilizer sources and promise to greatly simplify fertility management on these highly leachable soil mixes as well as other turf areas.

The past ten years have seen the development of urea-formaldehyde, which resembles organic nitrogen sources in many respects. Two new materials still in the development stage approach fertility control through different principles. In one promising process soluble, inorganic fertilizers are coated with a membrane which permits the minerals to diffuse out slowly. By regulating the thickness of the coating the rate of release can be regulated. Extensive laboratory and greenhouse testing has shown that a single application of this material could be expected to supply minerals at a relatively uniform rate for periods of about three to six months in spite of heavy leaching.

The other development is nitrogen minerals of low solubility-metal ammonium phosphates.These minerals have limited solubility and supply nitrogen by slowly dissolving. Preliminary information shows that these minerals can be expected to supply nitrogen relatively uniformly for prolonged periods of time and be resistant to leaching.

These new developments appear to offer revolutionary prospects in the fertility management of turfgrass and to increase the feasibility of the special purpose mixes.

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