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WATER-SOIL-PLANT RELATIONS

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With irrigation -- and where necessary, with drainage -- the farmer can exercise greater control over soil moisture than over any of the other soil physical factors.

Water held in the larger pores in most good agricultural soils drains away within a few days after an irrigation or heavy rain leaving the soil at a moisture content called field capacity. Plants growing on the soil will extract water, and if none is added plants will ultimately wilt. The moisture content at which that occurs is the wilting point. The water held by a soil between field capacity and the wilting point is called the available water. Various soils retain different amounts of water at field capacity and wilting point; therefore, they have different water capacities.

Existing viewpoints on soil moisture-plant growth relations and the probable influence of plant, soil, weather, and several miscellaneous factors on these relations are illustrated by a series of schematic diagrams. ***Most*** of these diagrams illustrate plant growth responses as available soil moisture is depleted within one irrigation cycle.

Under some conditions plants can apparently obtain a supply of water with equal facility between field capacity and the permanent wilting percentage as illustrated by the first diagram. This represents the view that the rate of plant growth is not diminished over the available range or, that no measurable increases in rate of growth are obtained by irrigating until the soil moisture falls to near the wilting point. The question mark indicates some uncertainty as to just when some plant response may be detected near the wilting point.

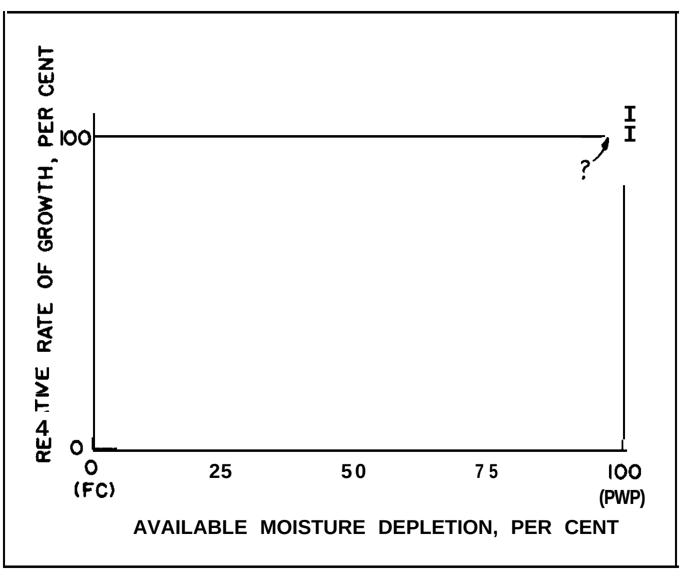

FIGURE 1

On the other hand, it is often maintained that plant growth diminishes progressively as the soil moisture content falls below field capacity with growth ceasing at the wilting point -- as illustrated in the second diagram -- but this more water, more growth idea finds little support among research workers.

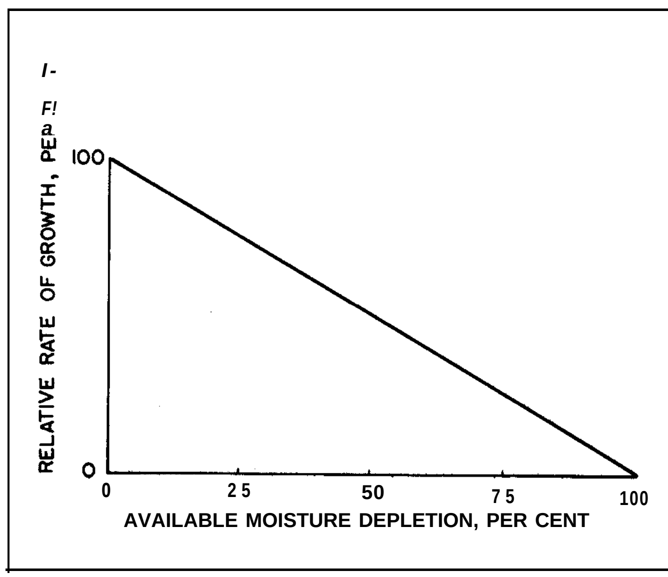

FIGURE 2

The availability of soil moisture is now frequently described in terms of soil moisture tension, which is dependent upon surface forces, and in terms of total soil moisture stress, which includes surface and other forces arising from the presence of solutes in the soil solution. The following diagram illustrates the increase in soil moisture stress in four nonsaline soils of different textures -- sands to clays -- as the available moisture is depleted from field capacity to the wilting point.

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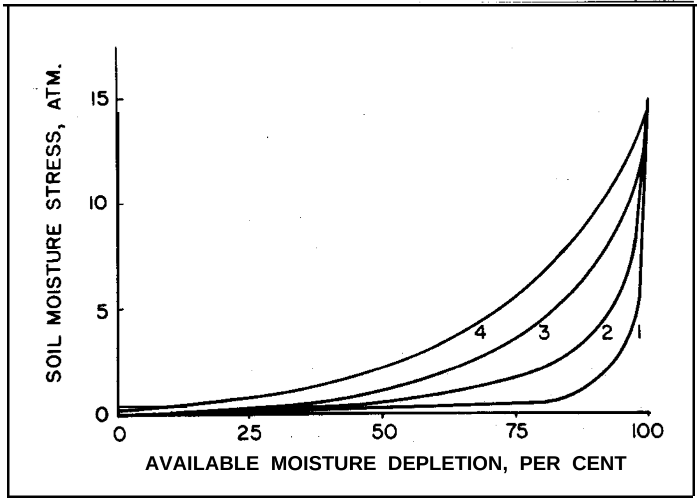

FIGURE 3

Excess salts in saline soils appear to influence plant growth in several ways including possibly an effect on water availability. Moisture content-soil moisture stress relations for a given soil to which increasing amounts of soluble salts had been added are given in the following graph-

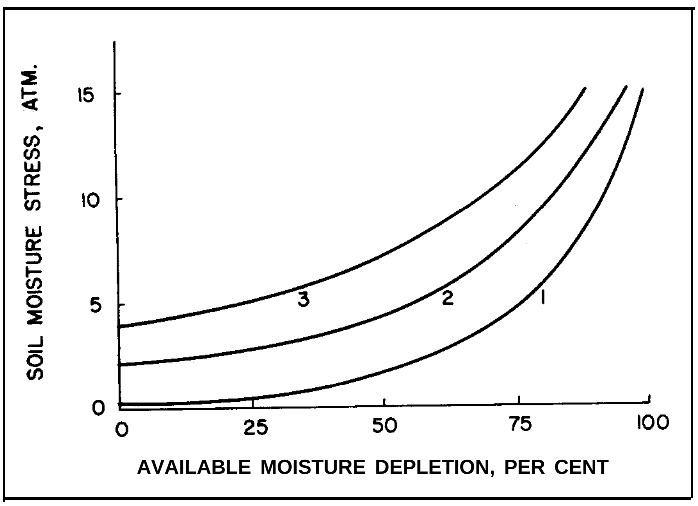

FIGURE 4

The theory that plant growth is a function of soil moisture stress is next expressed diagrammatically. If such a relationship exists, little retardation in growth on the nonsaline sandy soil would be expected until nearly all the available water had been depleted -- curve 1 -- but on the nonsaline clay soil illustrated some slowing of growth should occur after about 50% depletion-- curve 2. On the saline soil illustrated -- curve 3 -- a reduced growth rate would be expected even at moisture contents near field capacity, and growth would be expected to decline appreciably even in the upper half of the available moisture range.

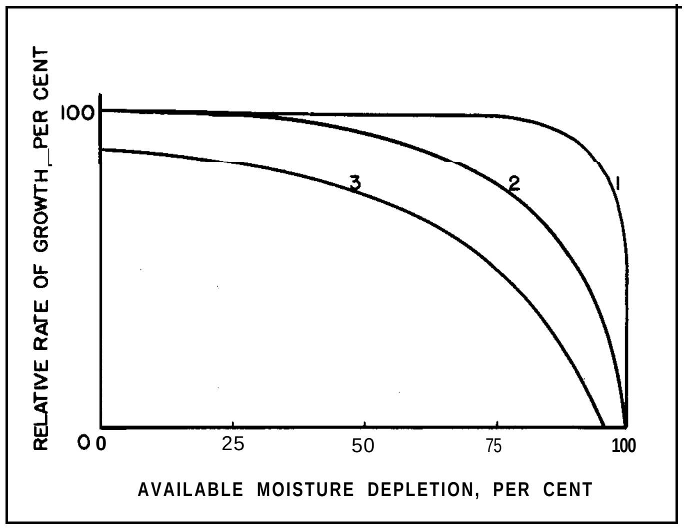

FIGURE 5

So far consideration has been confined to growth rates within one irrigation cycle. If moisture is equally available for plant growth over the entire available range during each irrigation cycle, then total growth over a period of such cycles will be independent of the level of moisture depletion permitted before irrigation within each cycle. This relationship is indicated by curve 1 of the next diagram. If, on the other hand, growth rates are related to soil moisture stress, then total growth over a period during which the stress varies may be related to some average stress condition -- curve 2 -- where the shape of the curve will depend on the soil moisture stress-moisture content curve for that particular soil. On the other hand, some field studies suggest that yields are

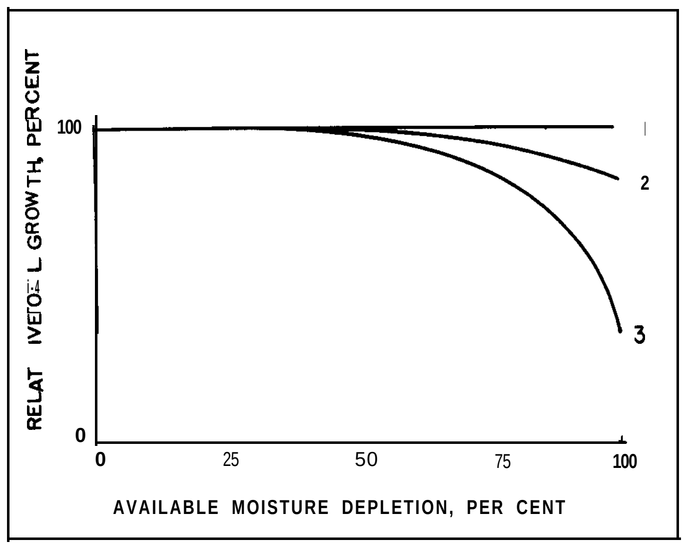

FIGURE 6

related to maximum stress prevailing prior to irrigation. In other words, high moisture stress values, though present for only a brief time interval, may have exaggerated

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effect on plant responses -- curve 3. Considerable experimental support can be found for each of these generalized relations. This situation indicates that moisture-growth relationships must be greatly influenced by the interplay of other factors which independently affect plant growth.

Plant Factors

Several different aspects of plant growth-- such as elongation of plant organs, increase in fresh or dry weight, and vegetative versus reproductive development -- are easily recognized. These commonplace processes are resultants of intricate combinations of many physiological processes which are probably not all equally affected by increasing soil moisture stress and an accompanying change in the internal balance of cells and tissues. Thus it is not surprising that various measurable aspects of growth do not respond in the same manner to moisture stress.

Data from studies on ladino clover illustrate this point. Some plant functions such as photosynthesis and respiration are relatively insensitive to moisture stress --

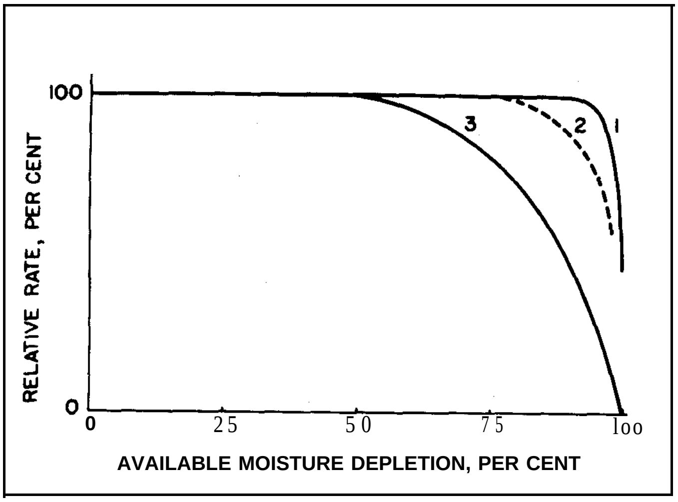

FIGURE 7

curve 1. Dry weight production may be more sensitive -- curve 2. Fresh weight yield and elongation of plant organs appear to be still more sensitive to moisture stress -- curve 3.

As plants are subjected to increasing moisture stress, appreciable shifts in the relative abundance of a variety of chemical constituents may occur in some plants. The percentage of sugar in cane and beets is raised by moisture stress. In tobacco increasing stress is reported to lower the sugar content and increase the percentage of nicotine and nitrogen in cured leaves. Thus the economic value of a crop may be influenced appreciably by moisture stress particularly during the period of maturation. Differences noted in the response of various growth processes to moisture stress point the way to the possibilities of so controlling the soil moisture stress through the growing season as to favor the production of that constituent or plant organ for which the plant is grown.

The effects of given soil moisture stress conditions on crops are often dependent upon the state of plant growth. Corn appears to be particularly sensitive to moisture stress during the tasseling period. Vegetative vigor is not necessarily associated with a comparable degree of productivity, as in the case of cotton where yields may be relatively higher on small plants than on tall or rank plants.

Another plant factor of extreme importance in determining the relation between measurable soil moisture stress and plant growth is the nature of the root system. Different interpretations of root development and of moisture conditions within the soil penetrated by roots contribute to the existence of contradictory views on water-soil-plant relations. Under favorable soil and growing conditions, most perennial crops develop well-branched root systems which thoroughly permeate the soil to a depth characteristic of the plant. Below this depth, the spatial density of absorbing roots diminishes until so few remain that moisture extraction can not be detected.

Moisture conditions within the expanding root system of an annual crop are even more complicated. In the seedling state, only a taproot or a few branched roots penetrate the soil. Some annuals rapidly develop a well-branched root system which permeates an ever-enlarging soil volume. Thus if the soil has been previously wet to field capacity through a considerable depth, these growing roots continuously come into contact with additional supplies of available water at low tensions. If the ro.ots are well-branched and grow rapidly enough, they may contact new supplies of readily available water with sufficient rapidity to replace the water lost from the leaves by transpiration. Because of rapid root growth, a crop such as watermelon on a deep alluvial soil may not respond to irrigation even though a relatively high soil moisture stress may develop within an ever-increasing soil volume. Other annuals send out a few widely spaced roots which leave large volumes of unexplored soil between roots particularly in the early stages of growth. Under such conditions soil moisture samples or even moisture indicating devices may give quite a false picture of moisture conditions at the root surface. Crops with sparse roots will respond to irrigations although the measured soil moisture stress may be quite low. As indicated in the following diagram, the sparser the roots the greater the likelihood that growth will be retarded by delaying irrigation. Very similar varieties of beans have shown different responses to irrigations, which are related to differences in their root development. Thus the fraction of the available moisture range which can be utilized before growth is checked will vary with root density.

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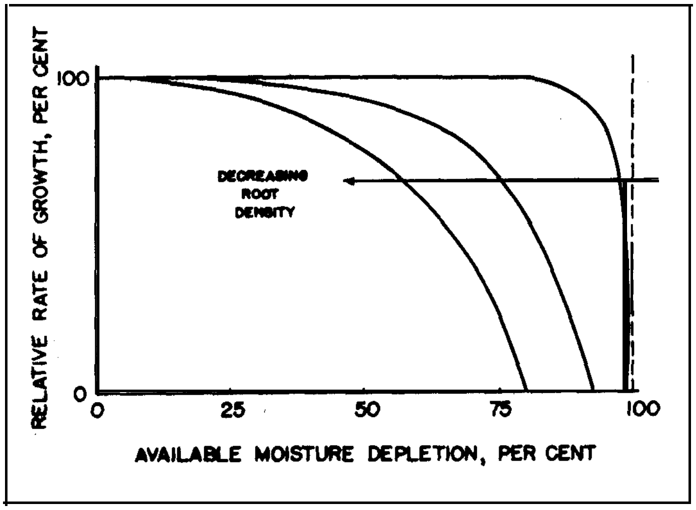

FIGURE 8

Until methods are developed to measure the moisture stress experienced by plants, it apparently will be necessary in the case of sparse-rooted crops to establish some rather arbitrary moisture depletion limits which unfortunately will depend on the stage of growth, growing conditions, and upon such other factors as soil and weather.

Where some roots extend beyond the bulk of the root system and absorb water against low soil moisture stresses, they may mask the effects of relatively high soil moisture stresses occurring over the remaining part of the root system. When most of the roots are confined to a given volume of soil and few roots extend out into relatively moist soil, the crop may be expected to be relatively sensitive to depletion of the available moisture. However, when a considerable number of roots extend into moist soil, depletion of the available moisture from the major part of the root zone may have relatively little influence on growth as indicated schematically at the top

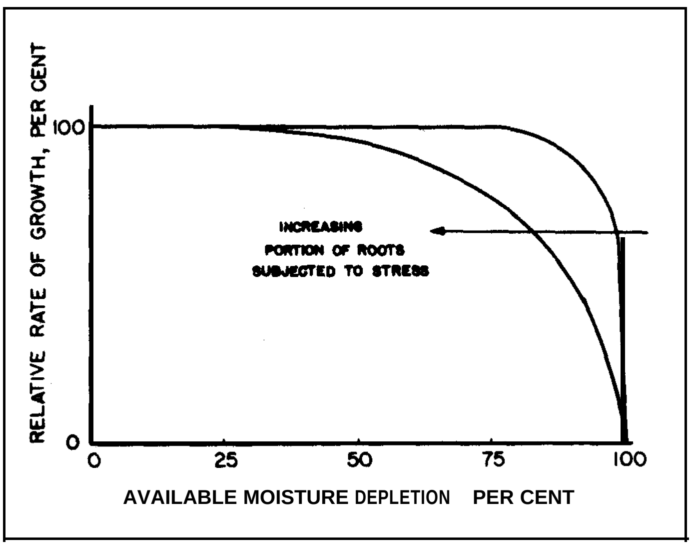

FIGURE 9

of the next volume. The presence of an unknown fraction of the total absorbing roots extending out into relatively moist soil makes it very difficult to evaluate the actual soil moisture stress to which the plant is subjected. Plants confined to containers or shallow soils may be expected to be quite sensitive to depletion of the available soil moisture.

Soil Factors

Any soil factor which affects root density or depth can be expected to influence the response of the crop to irrigation. Mechanical impedance, slow water penetration and poor internal drainage, and deficient aeration frequently are responsible for sparse and shallow roots. Soil structure, texture, and depth determine the total capacity of the soil for storing available water for plant growth. The total available moisture capacity within the root zone and the moisture-release characteristics of the soil are both important factors determining the rate of change in soil moisture tension or stress. Deep-rooted crops on deep soils usually show smaller responses to irrigations than shallower-rooted crops on the same soil. Crops growing on a soil in which 75%-85% of the available water is released at tensions below one atmosphere may be expected to show a smaller response to irrigations at a given moisture depletion level than the same crops growing on a soil in which less than 50% is released at such low tensions. The rate at which water can move to the absorbing root surface may play an important part in water-soil-plant relations.

A stable water table in the lower portion of the normal root zone of a crop may supply a considerable portion of the water absorbed by the roots and make the plants less responsive to moisture changes in the soil above the capillary fringe. On the other hand, a fluctuating water table may increase crop responses to early irrigation by restricting live roots to a shallow depth. Salinity may affect soil moisture-plant growth relations by decreasing moisture availability through increased soil moisture stress, by interfering with root growth and absorption through toxicity reactions, and by contributing to poor soil structure, which in turn influences infiltration, drainage, aeration, and root growth. Soil-borne plant diseases and nematodes, by reducing root surface, may cause crops to respond favorably to irrigations at seemingly very low moisture stress levels. Soil temperature also affects the rate of root growth and root distribution with depth.

The fertility status of the soil and possibly the depth distribution of some essential element may also determine the growth response of crops to irrigations at various moisture depletion levels, At low nitrogen levels, infrequent irrigations may produce as high or perhaps even higher yields than more frequent irrigations which cause some loss of limited nitrogen by leaching. However, when

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ample nitrogen is applied, this same crop may respond very favorably to the more frequent irrigation schedule. In soils where the available supply of some essential element is confined to the top soil, the drying out of the upper portion of the root zone may seriously retard plant growth even though the plant may still be adequately supplied with water from a less fertile subsoil. Fertility responses have complicated the interpretation of many soil moisture versus plant growth experiments.

Weather Factors

Weather conditions -- particularly light and temperature -- may so influence the growth characteristics of the shoot and root as to affect soil moisture-growth relations. Late-planted sugar beets which must develop roots during hot dry weather may fail to develop as dense or deep a root system as early seeded beets. Such beets are much more sensitive to depletion of available moisture than are the deep rooted beets planted early in the year. The length of the crop season before fall rains or frost may at least partially determine whether harvestable yields will be affected by imposing different soil moisture stress levels during the growing period.

Meteorological factors -- light, temperature, humidity and wind -- control the rate of water loss by transpiration from plant leaves and evaporation from the soil surface. Plant growth is probably dependent upon plant

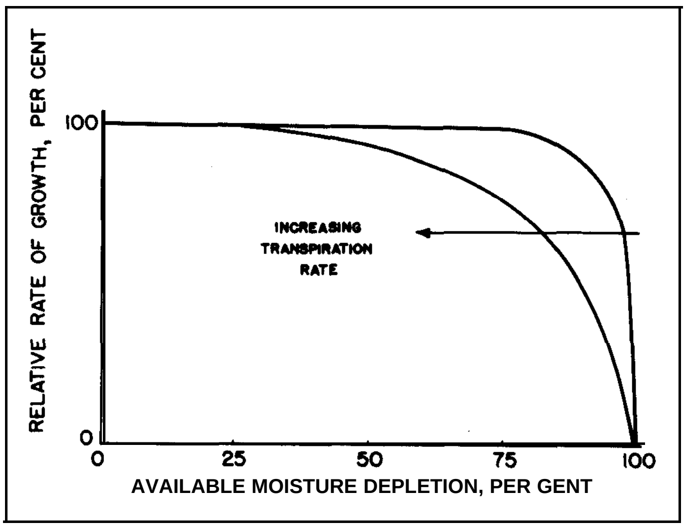

FIGURE 10

turgor, whose relation to soil moisture stress for different rates of transpiration needs to be explored. It can be reasoned that an increased rate of transpiration would lower the plant turgor corresponding to any given soil moisture stress. This would have the effect of causing growth to diminish at higher moisture levels as illustrated below. Much more work on this point is needed.

Miscellaneous Factors

Problems associated with insect control or harvesting may at times influence the apparent effects of soil moisture conditions on crop yields. The following study of forage and seed production by ladino clover provides an interesting example.

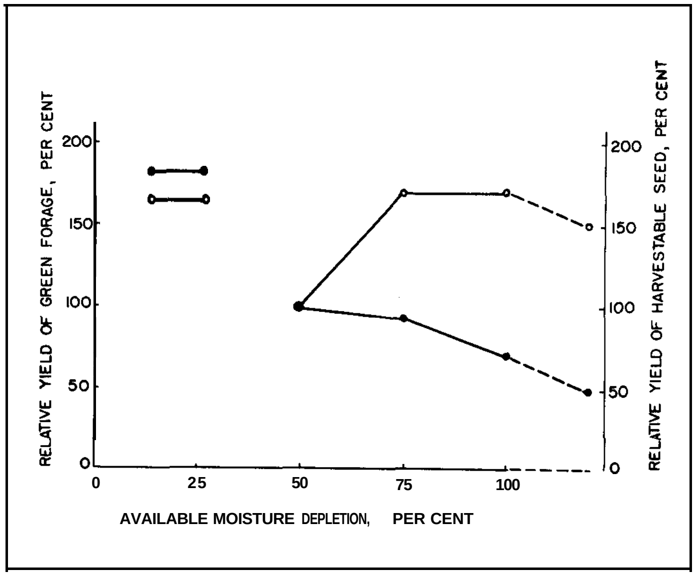

FIGURE 11

Increased dryness reduced forage yields but increased the harvestable yield of seed. The total seed actually produced by the clover also diminished with increased stress, but the higher humidityassociated with the wettest treatment caused such a serious preharvest loss of newly produced seed as to reduce the harvestable yields at the end of the season below those on the drier treatments. Some types of harvesting problems may affect the results of soil moisture-plant growth experiments more frequently than is realized.

Mention has been made of a sizable number of soil, plant, weather, and other miscellaneous factors which may influence the effects of various moisture depletion levels on plant growth or yield of some specific organ or constituent. When viewed against this background, it is not at all surprising that conflicting results have been obtained even in irrigation experiments involving some given crop. This discussion emphasizes the probable impossibility of finding any one generally applicable relation between crop yields and soil moisture depletion or soil moisture stress, at least as measured by our present methods.

Present information, meager though it is in many respects, may allow us to make some fairly accurate predictions whether growth or yield in given situations is likely to be unaffected by depletion of nearly all the available water as measured by present methods or is likely to be increased by irrigation at lower soil moisture stresses. The following two check lists may be helpful in anticipating the response of crops when given conditions prevail. It is not implied that all conditions must be present, nor is the relative weighing of each condition considered. If a given situation is described by some entries from both tables, prediction of response to irrigations will be much more difficult.

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Water-Soil-Plant Relations

SOME CONDITIONS WHICH WILL INCREASE OR DECREASE THE PROBABILITY THAT CROP YIELDS WILL BE REDUCED BY ALLOWING NEARLY COMPLETE DEPLETION OF AVAILABLE SOIL MOISTURE

Increased Probability (Relatively frequent irrigation desirable)	Decreased Probability (Relatively infrequent irrigation possible)
Plant:	
Shallow, sparse, slow-growing roots	Deep, dense, fast-growing roots
Fresh weight yield of vegetative organ desired	Dry weight yields of reproductive organ desired
Quality dependent upon size of vegetative organ	Harvest for content of sugar, oil, etc.
Soil:	
Shallow soil; poor structure impeding root growth	Deep soil; good structure
Slow infiltration and internal drainage; poor aeration	Good infiltration, internal drainage, aeration
Root disease, nematodes present	Large fraction of available water held at low soil moisture stress levels
Small fraction of available water held at low soil moisture stress levels	Nonsaline
Saline soils or water	F'ertility level low; nutrients distributed in profile
Fertility level high; nutrients concentrated in topsoil	Constant water table in reach of roots
Weather:	
Planted at beginning of hot dry season	Planted well ahead of hot dry season
Major growth period during hot dry season	Major growth period before hot dry season
High evaporation rates	Low evaporation rates

It is often questionable whether the increased yields sometimes obtainable with relatively frequent irrigations will pay for the added cost of water and labor. The following practical considerations all suggest the desirability of using irrigation water sparingly: maximum use of limited water supply, water and nutrient losses caused by deep percolation, danger of developing a drainage problem through overirrigation, maintenance of favorable soil tilth and, in some cases, obtaining high quality of marketable product. Frequent irrigations often aggravate the problems of plant diseases, insects and longevity in perennial crops. Although these considerations are of real importance in determining farm irrigation practices, their relative importance differs from place to place and even from year to year.

To assure a continuous supply of available soil moisture and to allow for unforeseen delays in irrigation or unusually dry weather, the irrigation farmer generally can not allow nearly complete available soil moisture depletion. To allow for a margin of safety, he should plan to irrigate while some available moisture still remains. The fraction of the total available moisture range which can be utilized with safety depends on a number of factors including crop rooting characteristics, the soil and the irrigation system. If, as illustrated below, a safety margin of 15% is made to meet the practical problems of irrigation under farming conditions, then a considerable portion of the differences predicted by the several current theories on water-soil-plant relations tends to disappear. However, to raise irrigation efficiency and to increase crop production, vigorous programs of research must be continued.

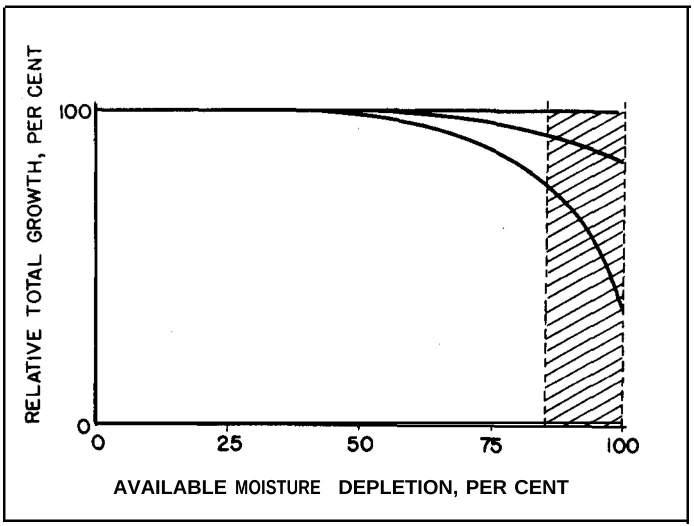

FIGURE 12

The studies on sugar beets were conducted by L. D. Doneen, and those on beans by L. D. Doneen, Professor of Irrigations, and D. W. Henderson, Assistant Professor of Irrigation, University of California, Davis.

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WATER PENETRATION OF SOILS

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The slow rate of water penetration into soils during irrigation is a serious problem, affecting -- to some degree -- a large portion of the major irrigated areas of California. In extreme cases there is a marked loss of production because it is difficult to supply crops with sufficient water even with frequent irrigation.

Slow water penetration is in reality several problems because it can be caused by different soil conditions. Effective means of coping with the problem depend on the cause. For example, one reason for slow water penetration is excessive sodium absorbed on the soil; a condition recognized for many years as alkali or black-alkali. Because sodium soils may be reclaimed by the use of mineral amendments, such as gypsum, there is a tendency to attempt the improvement of other kinds of impervious soils by applying similar materials. Such treatments are not effective, because they do not attack the underlying cause of the problem. All too frequently a quick, effective treatment cannot be found.

There are three additional causes of poor water penetration now recognized. One of them -- high clay content is well known. The limitations of clay soils in crop production may include slow penetration of water, but farmers have developed special practices which largely overcome this difficulty. One of the major problems remaining is the prevention of water-logging of the surface soil, which is frequently more open than the subsoil. Good surface drainage is essential, especially for crops susceptible to injury by root-rot diseases.

Two additional causes are soil compaction by traffic or tillage and unstable soils which run together on wetting. These conditions have been recognized comparatively recently, at least to the extent they are now known to occur.

Soil Compaction

Many soils which naturally absorb water readily have been compacted during land grading or farming operations. Two processes are involved -- compression of the soil by excessive surface traffic and compression or puddling by tillage implements. Both are more injurious if traffic or tillage occurs when the soil is moist, and both cause destruction of large pores in the soil necessary for rapid infiltration of water. Where compaction is extreme, entry of roots is retarded or even prevented.

Plow pans -- compacted layers a few inches thick just below plow depth -- have been recognized for years. They have caused no great concern because they can be broken up by increasing the depth of plowing and because they represent a small part of the total depth of the root zone. More intensive farming, heavier machinery, and in some cases deeper tillage have deepened the compact zone so that it may extend from the soil surface or the bottom of the tilled layer to an over-all depth of 18"- 24" below the surface. This greatly increases the seriousness of the problem.

Highly compacted soils can be recognized by experienced observers by digging or probing, especially if the soil lying below the compact zone is otherwise similar. Comparisons with the same soils in uncultivated areas such as fence rows may be helpful. Compacted soils are hard even when moist, and when lifted with a shovel loams and clays tend to fracture in layers with edges parallel to the ground surface. When a clod is broken, the freshly exposed edges are comparatively smooth with few openings visible. Clay soils have the appearance of fine-grained shale, and sandy soils look like sandstone. Lesser degrees of compaction are harder to distinguish visually even though water penetration is seriously impaired, especially in sandy soils.

Compaction may be considered an abuse of the soil, and the best practice is to minimize traffic or tillage, or delay until the soil is dry. However, essential operations may have to be performed when the soil is moist and therefore susceptible to compaction. Shattering by subsoiling through the compact zone when the soil is very dry may substantially improve the soil and increase water and root penetration. The improvement may be very temporary if the soil tends to run back together or if it is soon compacted again.

Under the most favorable conditions shattering allows penetration of water and roots into the fractures formed, but leaves dense clods which roots can not readily ***grow*** into. It should be considered the first step only in soil improvement, the rest depending on natural processes such as slow penetration by roots, wetring and drying, and others. In general, soils compacted by traffic or tillage do not respond to application of soil amendments.

Soil management practices such as cover cropping, growing green manure crops, and crop rotation need more study on a long-range basis. One application of manure or growth of a single green manure crop does not in general improve water penetration into soils already made compact by traffic or tillage. It is possible that such practices carried out over a period of years will reduce the susceptibility of soils to compaction, but not to the degree that they will withstand abuse.

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Unstable Soils

Most soils have a tendency to slake and run together somewhat when dry clods are wetted rapidly, but usually they break down into aggregates consisting of several soil particles, and these aggregates resist further disintegration. But there are some soils which slake to the extent that no aggregates remain, and unless they are very sandy, water penetration is exceedingly slow. Apparently the basic cause is the failure of the clay fraction to cement coarser particles together.

The worst of these soils have certain characteristics by which they may be recognized. The first time a loose seedbed is flooded the soil slakes down until there is no trace of clods remaining. The surface is smooth and becomes hard on drying. Few cracks appear, and these are fine hairline cracks. It is difficult to dig, and yet the soil crumbles readily when a dry clod is crushed in the hand, with formation of an excessive amount of fine dust. Roadways become covered with a thick layer of powdery dust. There is almost no lateral movement of water from furrows even when the bottom and sides of furrows have not been compacted by tillage or traffic. These characteristics may also be determined by laboratory tests, and better tests may be available soon which will aid in the diagnosis of less serious problems.

More and more problems are being investigated which are caused by this condition. It is especially serious because the difficulty lies in an inherent characteristic of the soil which cannot be changed by any economical means known at present.

Diagnosing the cause or causes of slow water penetration into soil is important because there is no other way to determine whether or not a proposed treatment will be effective. Some soil conditions respond to proper treatment, and a marked -- if only partial -- improvement results. Others have not yielded to any treatment yet developed. Research is in progress on the basic behavior of soils which will point the way in minimizing the problem, and these studies may suggest new, effective, treatments.

In the meantime, careful soil management is essential to keep conditions as favorable as possible. In cases where water penetration rates are not too slow, crop growth can be improved and yields increased by better management of irrigation water. A practice which is effective for deep rooted crops on deep soils is prolonged preirrigation for annuals or winter irrigation of perennials. If the poor physical condition of the soil does not seriously limit root development, a maximum amount of reserve moisture is stored in the subsoil. During the summer months when it is difficult or impossible to replenish the water in the soil as rapidly as it is used by the crop, the reserve subsoil moisture may determine whether or not there is an adequate supply of water.

In most cases not enough water can be stored in the soil to last throughout the season. Where water penetration is slow, more water can be applied by irrigating more frequently or by increasing the time the water is on the land surface at each irrigation. Both approaches have advantages and limitations. More frequent irrigation may be accomplished without any other change in the system or in practice, but has the disadvantage of higher labor costs. It may be an inadequate measure for the more difficult problems. Prolonged irrigation may require substantial changes such as converting from furrows to basins in which water can be ponded for long periods or using small furrows to insure better coverage of border strips with small streams. Irrigation of crops susceptible to injury or disease under prolonged irrigation can not be managed in this way, and the practice may encourage growth of water-loving weeds. However, such methods may be the only means of increasing the productivity of soils with very slow water penetration even though changes in cropping pattern or farming operations are required.

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