PROCEEDINGS

of the

WESTERN FARM ECONOMICS ASSOCIATION

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THE WEST IN A GROWING ECONOMY

Thirty-Second Annual Meeting

July 14-17, 1959

Logan, Utah

SOME CONCEPTUAL PROBLEMS IN DETERMINING THE PRODUCTION FUNCTION FOR WATER 1/

by

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Since the end of World War 11, agricultural economists in co-operation with physical scientists have devoted much time and energy to the exploration of production functions (response surfaces) for various factors of production. Various types and combinations of fertilizer and, in the field of animal nutrition, various feedstuffs were the variables considered most frequently in these investigations.

Water, one of our most basic production factors, has been almost completely absent from these discussions. The reasons for this absence do not appear to be economic, for water has always been a scarce factor in the Arid West, and it is rapidly becoming scarce in the more humid East. Rather, it seems--and this will become more apparent in the course of this paper -- that the difficulty of translating certain concepts used by agronomists into terms which can be used immediately in economic analysis might have stood in the way of greater cooperation between agronomists and economists in this particular area.

The increasing scarcity and the associated higher development costs of new water supplies, both here and in other arid parts of the world, make it necessary that we know more about the nature of water-input crop-output relationships. It is important from the viewpoint of efficient farm management, but even more so for water policy where the productivity of water within and between alternative uses--agricultural, industrial, receational, etc.--will be used increasingly as a criterion in the interpretation and reformulation of water laws and in the formulation of federal, state, and local government water development projects. 2/

1/ This paper is based on research undertaken under Project 1492 of the California Agricultural Experiment Station. This phase of Project 1492 is supported by the Water Resources Center. The author is indebted to S. V. Ciriacy-Wantrup, M. F. Brewer, D. W. Henderson, Martin R. Huberty, V. W. Ruttan, Stephen C. Smith, and D. W. Thorne for their constructive criticism.

2/ See, for example, Marshall, Hubert R., "The Evaluation of River Basin Development," Law and Contemporary Problems, vol. 22, no. 2, Spring, 1957, pp. 237-257.

We may assume that the economist is familiar with the implications for his analysis which derive from the empirically determined shape of the production function. For the noneconomist reader, it may suffice if we make the very general remark that, for purposes of determining an economic optimum, we are primarily concerned with the effects of each additional unit of input--which might be 1 acre-inch of water in our case--on production. As long as the value of the production increase resulting from one additional acre-inch of water, let us say, is greater than the cost of that acre-inch--plus associated costs like labor, etc.--it pays to use more water. Or, conversely, as long as the productivity of an additional unit of water in one use is higher than in other uses, it pays to change the present allocation until no further improvements are possible. In order for an economist to make specific policy recommendations of this nature, he must have an estimate of the effect of each additional unit of water on production. In more technical jargon, he must know the parameters of the production function of water in all those occupations in which this resource is used.

In the following discussion, we will (I) define a number of concepts used by agronomists in their discussion of the soil water regime and the relationship between water and plant growth; (II) consider a particular theory of plant response to water which has dominated the thinking of agronomists in the past; (III) relate this theory to the law of diminishing returns; and, finally, (IV) consider the law of diminishing returns and the possibilities for its empirical determination in a dynamic setting, namely, over the whole irrigation cycle. 1/

In the course of this discussion, it will become apparent that agronomists have, on the whole, given up the idea of trying to determine a production function for water simply by applying various quantities of it on a number of plots and measuring the resulting production response. Instead, they have concentrated on finding plant-water relationships which are in a sense, independent of soil type and, as we will see, also of water quantity. I believe that a clearer understanding of the motives behind this development and its consequences for purposes of economic analysis will be helpful in future cooperative research efforts in this particular area.

I

Field capacity, moisture equivalent, wilting point, and moisture tension or moisture stress are fundamental terms when a soil or irrigation scientist discusses plant and soil water relationships. What do these terms mean?

1/ Many of the basic ideas and much of the technical literature underlying this article were suggested in a review article by Kramer, Paul J., "Soil Moisture in Relation to Plant Growth," Botanical Review, vol. 10, November 1944, pp. 525-559.

Field Capacity is defined as the amount of water a soil will hold against gravity when allowed to drain freely. This point is usually reached in a well-drained soil about 48 hours after the irrigation is completed.[1]

The wilting point, also called permanent wilting precentage or wilting coefficient, designates a soil moisture content at which plants growing in that soil become permanently wilted and do not recover overnight.[2] Once this point is reached, no further growth will occur, which means plants are unable to extract more moisture from the soil than they lose through transpiration. The total amount of water left in the soil when the wilting percentage is reached depends mainly upon soil qualities, which will be explained below. Plant species and age of plants have surprisingly little to do with the occurrence of the wilting point, although the ability to survive in soil whose moisture content is materially below the wilting point varies considerably between different plant types.

Moisture tension or moisture stress is a measure of the force with which water particles are held by a particular soil. It has become a very widely used concept, although, and maybe because, it says nothing about the total amount of moisture which is present in a given soil volume. The relationships involved can be explained intuitively in the following way: Imagine the clay particles in a soil which has been wetted to field capacity as being surrounded by a film of water which itself is made up of a large number of water particles. Those water particles which are close to the surface of the clay particles are held relatively tightly, and those further removed from that surface, relatively loosely, yet with a force which must at least equal the pull of gravity. The tension on the soil moisture at field capacity lies within the range of 0.1-0.4 atmospheres.[3] As plant roots begin to remove soil moisture, they will first absorb these particles which are relatively loosely attached to the surface of the clay particles. After these loosely attached water particles have been removed, the moisture tension will begin to increase, that is, plants have to extract water which is held more tightly. As this process continues, a point -- the wilting point -- will be reached where the amount of water that plants are able to extract is exactly the amount they lose through transpiration. Finally, the power of roots to extract moisture becomes less than the power of clay particles to retain soil moisture, and the plant gradually dies. Soils with a large proportion of clay particles (clay, heavy loams), representing a greater surface area per volume of soil, will in general hold a greater total quantity of water at a given moisture tension than light soils (sands, sandy loams). Also, the range

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1/ Thorne, D. W., and H. B. Peterson, Irrigated Soils (2nd ed.; New York: The Blakistone Company, Inc., 1954), p. 34.

2/ Briggs, L. J., and H. L. Schantz, The Wilting Coefficient for Different Plants and Its Indirect Determination, (Washington: Govt. Print. Off., 1912). (U. S. Bureau of Plant Industry Bulletin No. 230.)

3/ Richards, L. A., and L. R. Weaver, "Moisture Retention by Some Irrigated Soils as Related to Soil Moisture Tension." Journal of Agricultural Research, vol. 69, pp. 215-235.

of readily available moisture, which is the same as the difference between field capacity and permanent wilting point, is relatively wide for clays and relatively narrow for sandy soils. 1/

The idea of relating plant growth first to moisture tension and only later and indirectly to water quantity, rather than trying to relate the two directly, has been a great step forward for the agronomist who is interested primarily in finding the general relationship between moisture conditions and plant growth. The introduction of the concept of moisture tension has enabled him to construct such a relationship which is in a sense independent of soil type and water quantity, the idea being that once this general relationship is known it is relatively simple to determine, on the basis of known moisture stress curves, the water quantity required to fill a particular soil to field capacity. In a later section (IV), we will try to assess some of the implications of this particular development for economic analysis. Before we do that however, it will be useful to consider in more detail certain aspects related to the movement of water in a soil.

II

In a long series of experiments conducted primarily in the Central Valley of California, Adams, Veihmeyer and Hendrickson, and

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1/ In addition to soil texture and clay type, there are other factors influencing the water-holding capacity of soils. Parks, W. L., in "Methodological Problems in Agronomic Research Involving Fertilizer and Moisture Variables," Methodological Procedures in the Economic Analysis of Fertilizer Use Data (Ames: The Iowa State College Press, 1956), p. 115, lists them in the following order:

1. Organic matter
2. Osmotic effects
3. Total pore size and pore size distribution
4. Depth of soil profile

There are some rare instances therefore, where a sandy soil may actually have a greater water-holding capacity than a heavy soil due to the influence of factors other than soil texture and clay type. (Cf. Thorne and Peterson, op. cit., p. 48.)

others 1/ concluded that, between wilting percentage and field capacity, plants extract the soil moisture necessary for their continued growth equally well. 2/ At first sight, this theory seems to be in sharp contradiction to the law of diminishing returns held in such high esteem among economists. Obviously, no plant growth can occur below the wilting percentage, and above that point the marginal physical product of increasing amounts of water input must be zero since plants are able to derive the soil moisture they require regardless of whether the soil moisture tension is that corresponding to wilting percentage (high) or that corresponding to field capacity (low). The physical production function corresponding to this point of view would, therefore, look like the one shown in Figure 1.

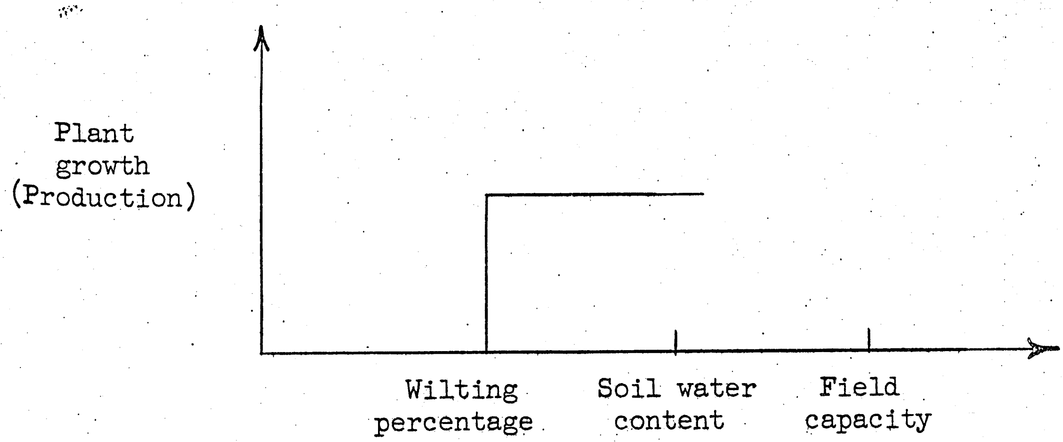

Figure 1

Schematic Production Function Illustrating the Results of Irrigation Experiments Conducted in the Central Valley of California

1/ See, for example:
Adams, F., et al., Cotton Irrigation Investigations in San Joaquin Valley, California, 1926-1935 (Berkeley: 1942), 93p. (California Agricultural Experiment Station Bul. 668.)
Hendrickson, A. H., and F. J. Veihmeyer, Irrigation Experiments with Peaches in California (Berkeley: 1929). (California Agricultural Experiment Station Bul. 479.)
Hendrickson and Veihmeyer, Irrigation Experiments with Prunes (Berkeley: 1934), 44p. (California Agricultural Experiment Station Bul. 573.)
Hendrickson and Veihmeyer, "Irrigation Experiments with Grapes," Proceedings, American Society of Horticultural Science, vol. 28, 1931, pp. 151-157.
Hendrickson and Veihmeyer, "Responses of Fruit Trees to Comparatively Large Amounts of Available Moisture," Proceedings, American Society of Horticultural Science, vol. 35, 1937, pp. 289-292.

2/ For opposing points of view, see Magness, J. R., et al., Soil Moisture and Irrigation Investigations in Eastern Apple Orchards (Washington: Govt. Print. Off., 1935). (U. S. Department of Agriculture Technical Bulletin 491.) Also, Baver, L. D., Soil Physics (3rd ed.; New York: John Wiley and Sons, Inc., 1956), especially pp. 290 and 306.)

The fact that water is equally available between these two points is explained by the fact that the force which it is held by soil particles changes relatively little between field capacity and wilting point; in particular, the soil moisture tension in most soils does not exceed 1 atmosphere until most of the available water is removed. 1/ Once the neighborhood of the wilting point is reached, however the soil moisture tension increases very rapidly and further growth is seriously retarded.

From the viewpoint of the economist, the implications of these results are obvious: Unless water and inputs associated with water application are free goods, profit is maximized only if the water application is kept just above the wilting point.

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The question now arises; Is it physically possible to control or maintain soil moisture at this particular "economocally optimum" level? The answer to this question appears to be negative. Kramer, 2/ reviewing the literature which deals with the experimental control of soil moisture points out that it is impossible to wet any soil mass to less than its field capaxity. In particular, he refers to the work of Veimeyer 3/ and Schantz. 4/ who came to the conclusion that, if a small quantity of water applied to a mass of dry soil, the uppermost layer is filled to field capacity while the rest of the soil remains uneffected. This phenomenon is explained by the fact that, as long as there are soil particles in the upper layer of soil whose moisture-holding capacity is not yet exhausted, no, or very little, moisture will be released to percolate to deeper soil layers. As more moisture is added, the soil is wetted to greater depth; however, the wet layer above will always be seperated from the dry layer below by a very sharp line of demarcation. These considerations lead irrigation scientists to the conclusion that there is no satisfactory way of keeping the moisture content of any volume of soil controlled below its field capacity. The moisture content of any particular layer of soil can only be reduced through extraction by plants or evaporation.

With respect to the shape of the crop-response curve to water, these considerations are of considerable importance because they suggest the following; if only a very small amount of water is applied to a soil planted to a given crop, only the uppermost part of the soil will be wetted. Germination, root

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1/ Wadleigh, C. H., "The Integrated Soil Moisture Stress Upon a Root System in a Large Container of Saline Soil," Soil Science, vol. 61, 1946, p. 225

2/ Kramer, Plant and Soil Water Relationships (New York: Mc Graw-Hill Book Co., 1949), p. 94.

3/ Veihmeyer, "Some Factors Affecting the Irrigation Requirements of Deciduous Orchards," Hilgardia, vol. 2, no. 6, January, 1927, pp. 125-284.

4/ Schantz, "Soil Moisture in Relation to the Growth of Plants," Journal of The American Society of Agronomy, vol. 17, November, 1925, pp. 705-711 development, and plant growth being restricted to this layer of soil will be retarded; and the resulting yield response will be zero or, at best, a very small amount. As more water is applied, a second layer of soil will be wetted; germination and root development will be improved, and so will the resulting production. As this process is carried on, it should result in the production-response curve similar to that suggested by Mitscherlich 1/ and Spillman 2/ a curve which approximates, although due to experimental difficulties it may do this only in a discrete form, our usual concept of the law of diminishing returns illustrated in Figure 2. 3/

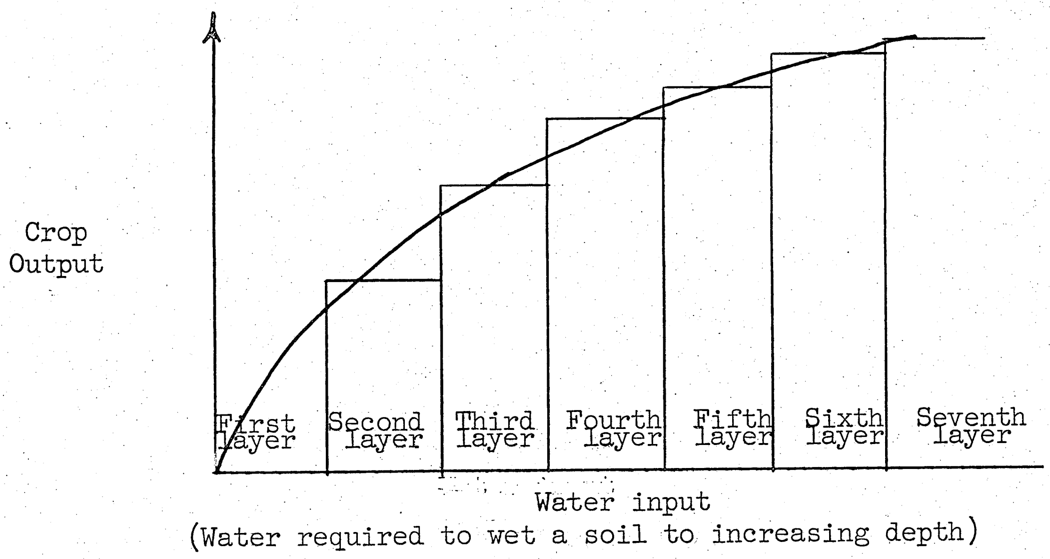

Figure 2

Hypothesized Crop Response Curve as Soil is Wetted to Increasing Depth

It is the crop-response curve understood in this context which is the basis for a great deal of empirical work carried out in the early part of

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1/ Mitscherlich, E. O., "Das Gesetz des Minimums und das Gesetz des Abnehmenden Bodenertrags," Landwirtschaftliches Jahrbuch, vol. 38, 1909, pp. 537-552.

2/ Spillman, W. J., Use of Exponential Yield Curves in Fertilizer Experiments (Washington: Govt. Print. Off., April, 1933), 67p. (U. S. Department of Agriculture Technical Bulletin 348.)

3/ This argument implies, of course a *ceteris paribus* assumption and does not mean that plant response is always proportional to the depth to which a soil is wetted. It has been pointed out to me by D. W. Thorne that studies both here and abroad have shown repeatedly that yields can be very high if only a shallow amount of soil is kept wet, provided that there is enough fertility in that shallow layer of soil.

this century 1/ and some recent efforts, one of which was reported not long ago in this Journal. 2/

IV

The foregoing discussion has treated the problem of determining crop response to changing quantities of irrigation water in a static framework only. In actual practice, however, soil and plant conditions are such that, in order to provide the crop with a relatively continuing water supply, it is necessary that the total water quantity be distributed in some way throughout the growing season. Theoretically, a certain quantity of water can be distributed through the season in an infinite number of ways, varying from all of it at one point in time--usually the spring of the year--to a distribution, which may be uniform or skewed, where smaller quantities are applied every week or even every day. With a given quantity of water, certain time distributions will produce a greater total value product than others, and over a certain range other production factors--labor and capital--which differ for each time distribution, are subsitutable for water quantity in the sense that the same total physical product can be produced with a smaller quantity of water but a "better" time distribution and vice versa. 3/

1/ See, for example, Widtsoe, John A., and L. A. Merrill, The Yields of Crops with Different Quantities of Irrigation Water (Logan: 1912), 119p (Utah Agricultural Experiment Station Bul. 117.)

2/ Orazem, Frank, and Roy B. Herring, "Economic Aspects of the Effects of Fertilizers, Soil Moisture, and Rainfall on the Yields of Grain Sorghum in the 'Sandy Lands' of Southwest Kansas," Journal of Farm Economics, vol. XL, no. 3, August, 1958, pp. 697-708.

3/ The physical factors determining the optimum water quantity and irrigation frequency have been well summarized by Kramer in Plant and Soil Water Relationships, p. 102:

"The amount of water to be added at any one time and the frequency of irrigation depend on the texture and depth of the soil, the depth of rooting of the crop, and its rate of transpiration . . . sandy soils must be irrigated more frequently, although they require less water per application than do clay soils. . . Shallow rooted crops such as sweet corn, onions, and lettuce, require more frequent irrigations than do such deep rooted crops as tomatoes, watermelons, and pumpkins. The rate of evaporation from the soil surface and the rate of transpiration also affect the frequency of irrigation, because they determine the rate of removal from the soil. Water use is much lower during cool, cloudy weather than during hot, clear weather; and young crops use less water than is needed by older crops, having a larger leaf area. Irrigation should be adjusted accordingly."

There are, of course, other factors which usually determine irrigation frequency, notably such extraneous factors as institutional arrangements whereby a farmer in an irrigation district can only receive water delivered to his headgate at certain intervals. Since we are primarily concerned with the problem of determining a physical production response curve, we can abstract from some of these factors.

The fact that most soils require that irrigation water be applied at intervals throughout an entire irrigation season explains the importance which irrigation scientists have attached to the problem of determining that moisture percentage which in a particular soil and for a particular crop constitutes the wilting point or the wilting percentage as it is sometimes called. Assuming, for the time being, that the argument regarding the equal availability of water to plants between field capacity and the wilting point is correct and, secondly, that a soil moisture content which is kept below the wilting percentage for any extended period time is undesirable for continued plant growth, then the wilting point can be taken as the only relevant signal indicating when it is time to apply irrigation water.

The determination of that water content which constitutes the wilting percentage in a particular soil is surrounded by a great number of problems, mainly because the moisture content of a given soil volume does not change uniformly after an irrigation. 1/ The reasons for this lack of uniformity are twofold: (1) The moisture content of the upper layers of the soil profile will be reduced more quickly to the wilting percentage through evaporation, while considerably more soil moisture remains in lower soil strata, and (2) in those parts of the soil profile which contain the heaviest concentration of plant roots, soil moisture tension will increase more rapidly, resulting in areas within the profile which contain much less available soil moisture than others. The almost complete absence of lateral or vertical movement of soil water in response to these relatively small differences in soil moisture tension, which result from plant root extraction, aggravates this problem. Richards and Wadleigh state in this connection: 2/

> The effective distance through which water in the available range can move toward the root is certainly of the order of inches and not feet. The pattern of moisture extraction is therefore largely a matter of the active root distribution. Root distribution . . . is mainly determined by the genetic character of the plant but is modified by plant spacing as well as by soil and climatic factors.

One might emphasize here that the availability of water may, within the limits imposed by genetics, also be a major factor determining the extent of a plant's root system. Thorne and Peterson point out in this connection that ". . . the growth of roots is generally considered more important than water movement in bringing new supplies of water to roots for soils below field capacity." 3/

Since the roots of a crop extend vertically through a certain part of

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1/ For a discussion of the methods used for measuring soil moisture tension see Thorne and Peterson, *op. cit*.

2/ Joint Committee on Soil Tilth, American Society of Agronomy, and American Society of Agricultural Engineers, *Soil Physical Conditions and Plant Growth*, edited by Byron T. Shaw (New York: Academic Press, Inc., 1952), vol. II, p. 85.

3/ Thorne and Peterson, *op. cit*., p. 45.

the soil profile, and since the moisture tension within this profile does not change uniformly after an irrigation, it follows that the soil moisture condition which generates wilting is not a single point but rather a certain distribution of soil moisture throughout the profile. Thus, when we look at soil water relationships in a dynamic setting we arrive at the following conclusions: (1) Within any one layer of soil moisture tension will be an increasing function of time t, and (2) at any one period of time, moisture tension within the soil profile--between layers--will be a decreasing function of depth x. These relationships are illustrated schematically in Figure 3, where moisture tension is plotted on the vertical, depth of soil on the horizontal axis, and different time periods after the date of irrigation are represented by curves t_o (field capacity), ..., t_n.

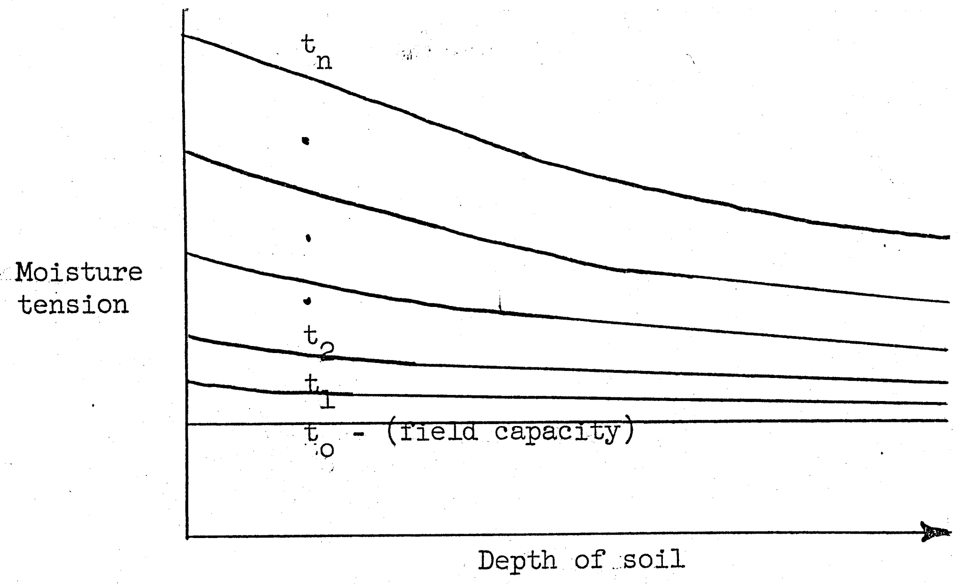

Figure 3

Schematic Illustration of the Relationship Between Soil Moisture Tension, Time and Depth of the Soil Profile

From an analytical point of view, that is, for purposes of determining crop output as a function of various soil moisture conditions, it would be extremely cumbersome to work with distributions of this kind as independent variables. To overcome this difficulty, Wadleigh 1/ and Taylor 2/ have suggested methods of combining these distributions into a single number by means of a concept which they have called "integrated moisture stress." The

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1/ Wadleigh, op. cit., pp. 225-238.

2/ Taylor, S. A., "Estimating the Integrated Soil Moisture Tension in the Root Zone of Growing Crops," Soil Science, vol. 73, 1952, pp. 331-340.

method suggested by Wadleigh has particular reference to saline soils, which are very common in the western United States and many other arid parts of the world. In his system, the total soil moisture stress S at any one point in time is expressed as a linear function of the soil moisture tension T and the osmotic pressure π, the latter resulting from the presence of salts in the soil. The relationship is expressed in Equation (1)

$$S = T + \pi . \qquad (1)$$

T is a decreasing function of depth, but π, as a result of leaching, which leads to greater salt concentrations in lower soil strata, is an increasing function of depth, and so the two forces tend to make the total soil moisture stress uniform throughout the soil profile. With this in mind, Wadleigh makes the assumption that, in certain saline soils, S is no longer a function of depth but only a function of time. By integrating S with respect to time as in Equation (2)

$$A = \int_{t_o}^{t_x} S dt, \qquad (2)$$

he obtains the integrated atmosphere days A, that is, the sum total of the different stresses exerted each day during the irrigation interval. t_x represents the number of days in the irrigation interval, and $\frac{A}{t_x}$ represents the average soil moisture stress during the irrigation interval. Either A or $\frac{A}{t_x}$ can then be used as the independent variable in the determination of a physical production function.

The method suggested by Taylor is similar but more general, inasmuch as it considers both time and depth variation of soil moisture tension expressed in a general form as follows:

$$T = F(x,t), \qquad (3)$$

where T again denotes the total soil moisture tension, x is the depth below the surface, and t is time. In this system, it is first necessary to express soil moisture tension with respect to depth as a function of x as in Equation (4)

$$T_i = f(x), \qquad (4)$$

and with respect to time as in Equation (5)

$$T_j = g(t). \qquad (5)$$

After combining these two equations into (6)

$$F_{ij} = F(x,t), \qquad (6)$$

and integrated soil moisture tension is expressed by the double integral (7)

$$T_r = \int_{t_o}^{t_x} \int_{x=d_o}^{x=d} T_{ij} dx dt,$$

Where T_r represents the integrated soil moisture tension in the root zone. Both Wadleigh and Taylor show in detail how these integrals are evaluated and empirically approximated, and the reader is referred to these publications for a detailed exposition of the procedures used.

Since these methods have been developed, a number of experiments were conducted in which crop output was related to variations in integrated moisture stress. 1/ It is not the purpose of this paper to restate these experimental results except to mention that all of these studies show higher production--in particular, more vegetative growth 2/ for those moisture treatments with low integrated moisture stress. These experiments leave little doubt about the existence of the law of diminishing returns in response to changes in integrated moisture stress--or rather its inverse 3/ if only the moisture stress is allowed to vary over a wide enough range.

How can these experiments which involve variations in integrated moisture stress be evaluated for purposes of economic analysis? In answering this question, it is important to keep in mind that there will not be a very high correlation between the number of irrigations and the total quantity of water necessary to keep the moisture stress of a given soil volume within specified limits. This means that, as the integrated moisture stress is allowed to rise, it will not be accompanied by a proportional decrease in water quantity. The reason is that it takes less water *per irrigation* to bring a given soil volume up to field capacity if only a small variation in moisture stress is allowed as compared to a soil whose moisture content was allowed to fall much lower. Due to unavoidable wastes and more frequent opportunity for evaporation from the soil surface, the more frequent irrigations will, of course require a

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1/ See, for example, Wadleigh, H. C. Gauch, and O. C. Magistad, *Growth and Rubber Accumulation in Guayule as Conditioned by Soil Salinity and Irrigation Regime* (Washington: Govt. Print. Off., November, 1946), p. 34. (U. S. Department of Agriculture Technical Bulleton No. 925.) Also, Wadleigh and A. D. Ayers, "Growth and Biochemical Composition of Bean Plants as Conditioned by Soil Moisture Tension and Salt Concentration," *Plant Physiology*, vol. 20, 1945, pp. 106-132.

2/ There are, however, some interesting instances, as was shown recently in a number of cotton experiments in California, where the high tension treatments resulted in considerable reductions in vegetative growth but had little effect on the yield of cotton as such. See, for example, Stockton, J. R., and L. D. Doneen, "Factors in Cotton Irrigation," *California Agriculture*, vol. 11, no. 4, April, 1957, p. 16.

3/ It really does not matter in principle how we plot the production function. Since we expect low yields to occur as a result of high moisture tension treatments, we would have to plot yield against the inverse of moisture tension in order to produce a response curve which has the shape to which we are accustomed from the literature.

greater total quantity of water than the less frequently irrigated plots. This quantity might accidentally turn out to be a linear function of the number of irrigations, which should not be construed to mean that all of the water has been made available to plants. Differences in production response resulting from such an experiment might, therefore--speaking again in terms of water actually made available and ruling out waste--be due not so much to differences in the total quantity of water applied but rather to its better time distribution. But what is time distribution from the viewpoint of the economist? It is simply the application of labor and capital, which means that, if we hold constant the soil mass which is to be wetted, then variations in integrated moisture stress which result from more frequent irrigations will be related much closer to labor and capital inputs than to water quantity per se. Significant variations in water quantity will be encountered only when we introduce variations in the depth to which a soil mass is to be wetted.

We can now summarize the principal arguments which have been advanced in this paper: It has been pointed out that the production function for water can be thought of in two ways--first, in terms of the relationship between output and the use of different water quantities, reflected mainly in the depth to which a certain soil mass is wetted, and, secondly, in terms of the relationship between output and the existence of various moisture stress conditions which are allowed to occur between irrigations. The production function understood in the first context underlies much of the agronomic work carried out in the early part of this century. More recently, soil and irrigation scientists have placed greater emphasis on determining a production function understood in the second context. In these experiments, there is little variation in water quantity and in depth to which a soil is wetted, but greater emphasis on the problem of determining the optimum distribution of moisture throughout the growing season. This second type of production function can be interpreted in terms which are economically meaningful if changes in seasonal distribution of water are thought of as reflections of variations of associated labor and capital inputs rather than in terms of variation in water input.