W. L. PARKS
University of Tennessee

Chapter 7

Methodological Problems in Agronomic Research Involving Fertilizer and Moisture Variables

MANY fertility experiments have been discarded or were never completed because soil moisture deficiency eliminated any chance for the different fertilizer treatments to exert their full potential. In fact, many fertilizer experiments conducted today tend to add more information about yearly variation to crop response due to season than they do to defining the actual limit of the fertilizer treatments. During years of adequate available moisture, the yield differences are often quite marked and a high production level is attained. However, during years of extreme drought little or no increase may be obtained, and the response to a given increment of fertilizer is much less than under conditions of better available moisture conditions. Plant nutrition is related in many ways to soil moisture, both directly and indirectly. This chapter presents some of the factors involved in the mineral nutrition of plants under variable moisture conditions.

The Soil System

A representative silt loam surface soil has been described by Lyon, Buckman, and Brady (30) as having 45 percent mineral matter, 5 percent organic matter, 25 percent water, and 25 percent air by volume. This means that the soil would have 50 percent of its space occupied by solids, the remainder being pore space that could be occupied by air or water or both. The volume composition values of four Tennessee Valley soils are given in table 7.1. These values do not deviate far from the average values presented by Lyon, Buckman, and Brady.

Soil particles possess the capacity to take up and retain moisture (8) which is distributed through the pore space of the soil and is held in the soil system by a combination of forces. It is possible under certain conditions for all of the soil pore space (except blocked pores) to be filled with water. Much of this water is unavailable for plant growth, however, as it is either lost through percolation or is held by the soil so tightly that the plants are unable to absorb it.

Figure 7.1 shows the volume composition of a Maury silt loam surface soil, and it may serve to illustrate the volume of the soil that is important in soil moisture-fertility relationships. The area A X B represents the larger pores of the soil. These pores are filled with

TABLE 7.1. Volume Percent Composition and Bulk Density of Four Tennessee Valley Soils

Soil Series	Sample Depth	Texture	Percent Pore Space	Percent Solids Mineral + Organic	Bulk Density
Maury	0-6"	Silt loam	50.9	49.1	1.38
	6-12"	Silty clay loam	49.8	50.2	1.47
Lindside	0-6"	Silt loam	47.7	52.3	1.43
	6-12"	Silt loam	49.8	50.2	1.38
Ennis	0-6"	Silt loam	56.7	43.3	1.25
	6-12"	Silt loam	54.4	45.6	1.32
Hartsells	0-6"	Fine sandy loam	54.0	46.0	1.31
	6-12"	Fine sandy loam	51.7	48.3	1.41

water during periods of heavy rainfall or heavy irrigation. However, this water is quickly lost through gravitational movement and is consequently of little use to plants. The area C X D represents that volume of water held by the soil so tightly that the plants are unable to extract

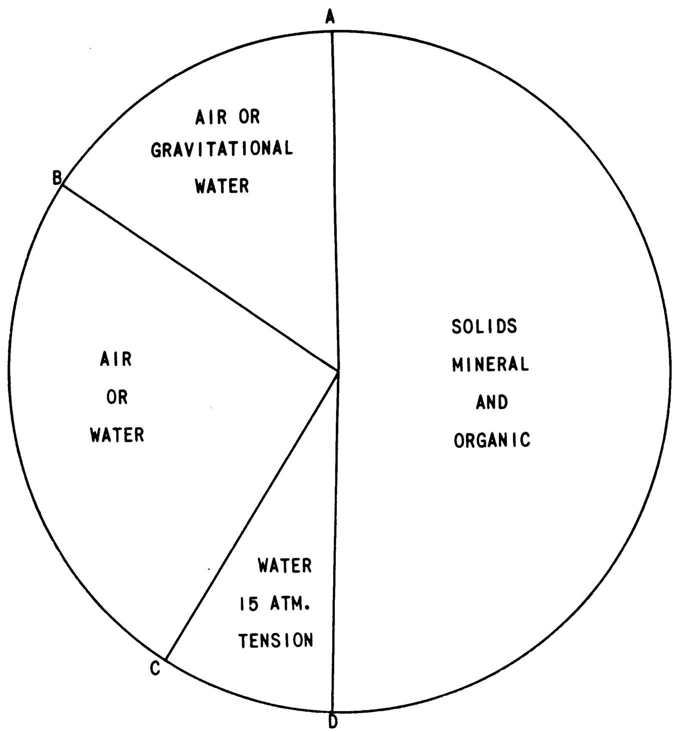

Fig. 7.1 — Volume composition of a Maury silt loam soil.

it from the soil. This is the moisture held under more than 15 atmospheres tension. Perhaps it is incorrect to say that plants are unable to extract this water from the soil because they can to a certain extent; however, they are unable to extract moisture from the soil in large enough quantities for normal physiological functions when the moisture is under a tension of 15 atmospheres or more. The area B X C represents that volume of a soil which may be filled by water or air. It is the moisture in this portion of the soil volume that is important in the growth and physiological behavior of crop plants. Point B could represent the field capacity and point C could represent the wilting point for the soil. The point for optimum growth of farm crops lies somewhere between B and C but is probably not very close to either B or C. The point for optimum growth may be different for different crops. The area A X D represents the mineral and organic portion of the soil. The size distribution and arrangement of particles, although they may vary quite widely for different soils, determine to a great extent the physical potentiality of the soil for crop production.

Moisture-Holding Capacity

There are several factors that determine the moisture-holding capacity and available moisture of a soil. Some are:

1. Texture and clay type
2. Organic matter
3. Osmotic effects
4. Total pore space and pore size distribution
5. Depth of soil profile

The effect of texture upon the moisture-holding capacity of a soil has been discussed by Richards and Wadleigh (40, 41). This effect is well illustrated by figure 7.2.

Note that for a given tension the heavier textured soils contain more water than the lighter textured soils. The bulk of available soil moisture in the loams and lighter textured soils has been depleted at tensions far less than 15 atmospheres, which is generally accepted tension corresponding to the wilting of plants in a soil system. This relationship may be of great economic importance in plant growth where moisture fertility relationships are involved.

The role which organic matter plays in the moisture-holding capacity of a soil is perhaps more indirect than direct. Jamison (23) concluded that organic matter did not increase the capacity of a soil to store available water except in sandy soils; however, the effects of organic matter on the structural development in a soil, its infiltration capacity, permeability, and other factors greatly aid its moisture-holding characteristics when considered in terms of crop production.

Osmotic Effects

The osmotic effects are those caused by soluble salts, exchangeable

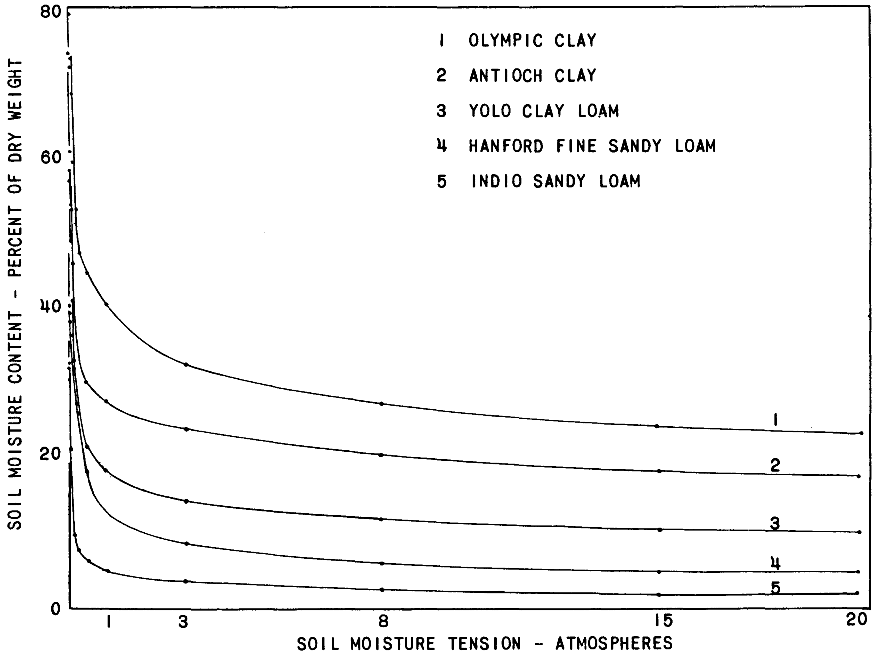

Fig. 7.2 — Curves showing the relation between the soil moisture tension and the moisture content of the soil. Richards and Wadleigh (40).

cations, and/or colloidal material suspended in the soil solution. These effects on the available moisture supply in a soil have been well illustrated (2, 29, 57). Increases in the salt and/or colloidal content in the soil solution will increase the permanent wilting percentage and thereby decrease the amount of water that the soil may retain which would be available for plant growth. White and Ross (60) have shown that an application of 1300 pounds of 3-9-3 fertilizer per acre to a Norfolk sandy loam increased the osmotic pressure of the soil solution to about 14 atmospheres. A similar application to a Cecil clay loam produced an osmotic pressure of only 3 atmospheres.

The total pore space is the factor that really determines the amount of water which may be found in a given volume of soil. It is this space which the water actually occupies. It is the pore size distribution that determines the relative amounts of the water which the soil will contain at different tensions. This property is determined by the texture, organic matter, and structural arrangement of these different components. The amount of water held by a soil, that is available to plants, depends upon the amount held per unit volume of soil. Thus, the depth of the soil explored by roots plays an important role in the total amount of water that may be available for plant growth within a given soil.

One very important factor in the moisture status of soils is the entry and movement of moisture into a soil (23, 45). The benefits of tillage, mulching, and crop cover upon water entry and movement in a soil are generally recognized. The slope of the soil is also important in determining the amount of water entry into a soil. This is especially true during periods of intensive rainfall. In cases where soil slope is an important factor in moisture entry into a soil, the infiltration capacity of the soil becomes increasingly important. A good example of this is the Dellrose soil on the slopes between the Highland Rim and the Central Basin in Tennessee and Kentucky.

One of the difficulties in evapo-transpiration studies is determining effective rainfall. A rainfall of two inches in an area may result in an effective rain of only one inch in a soil with some degree of slope. The colluvial soil adjacent to this area may receive over two inches, as it could receive runoff from adjacent areas.

Other factors play important roles in the moisture-holding capacity of a soil. However, many of these could be classified under one of the above factors.

Ionic Relations in a Soil System

The component in a soil that determines its ionic exchange capacity is the colloidal fraction. Although the silt fraction possesses some exchange properties, the magnitude of their effect on the total exchange capacity of a soil is relatively small. Organic matter accounts for considerable ionic exchange in a soil, even when present in small quantities.

Colloidal material is less than .002 mm in diameter. One of the properties of most soil colloidal particles is that they possess negatively charged surfaces and, when in a suspension, they are surrounded by a swarm of cations and anions that are in equilibrium within the system. Also surrounding these clay particles is a layer of water. The free energy of the vapor or liquid at the curved vapor liquid interface may be expressed as:

$$\triangle F = \frac{2 \sigma V}{R} .$$

When σ is the surface tension, V is the specific volume, and R is the radius of curvature (8). Essentially this means that water is held more tightly as the radius of curvature decreases. Thus, the work that must be done to remove the water is inversely proportional to the radius of curvature of the liquid-vapor interface. If a large amount of water surrounds the clay particle, as would be the case when the soil is near saturation, little work will be required to remove a small increment of this water, but the amount of work required to remove each successive increment of water gradually increases.

It must not be concluded that the resistance a soil offers to water extraction by plants is entirely related to the radius of curvature of the liquid vapor interface; many other factors are involved. Among these are the osmotic forces, the gravitational forces, and the electrical forces of the charged clay particles. Many terms have been used to express the total effect of these forces on the soil moisture, the most recent one being total soil moisture stress.

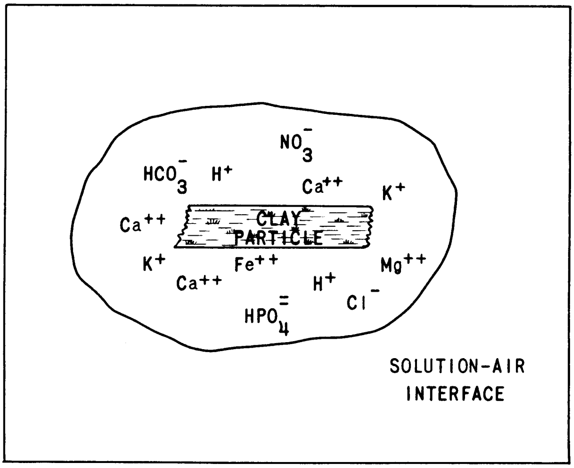

Fig. 7.3 — Clay particle surrounded by ion swarm.

Almost any surface possesses certain electro-chemical properties (1), and the surface of clay particles due to their structure is negatively charged. The magnitude of this charge and the water retention properties of clays are determined by their structure (3, 30, 31, 40, 41). Surrounding this charged surface, and in equilibrium with the soil solution, is an ion swarm. These ions largely constitute the nutrients that are absorbed and utilized by plants. Both cations and anions are contained in the ion swarm, and some of these may be "fixed" or absorbed on the surface of the clay particles (6, 54, 59). The extent of this fixation is determined by a number of factors. These will be discussed later.

Nutrient Absorption Under Variable Moisture Conditions

The soil system is made up of a number of particles, of various sizes, randomly distributed. Between the larger particles are the smaller particles. Surrounding all the particles is space that may be occupied by air or water. In order for plants to absorb nutrients they must extend roots through this air or water to contact the surface films of moisture surrounding the soil particles; it is in this film that the nutrients required for plant growth are found. Plants obtain certain of these nutrients through a process generally known as "contact exchange" (24), during which the plant root may absorb both cations and anions. Through normal respiration the plant root gives off CO_2, which unites with water to form H^+ and HCO_3^- ions. This maintains the electrostatic balance between cations in the soil solution and the negatively charged clay surface.

As the plant root absorbs nutrients from the surface of the soil particles, the equilibrium with the surrounding soil solution is disturbed. As a result, there is a net movement of other anions and cations toward the plant root and a net movement of H^+ and HCO_3^- ions away from the plant root. This exchange of ions results in a net increase in soil acidity.

Water is absorbed by the plant root, in addition to the mineral elements. As the moisture in the pores surrounding the clay particles near the root is utilized by the plant, there is a net movement of water toward this area from the adjacent pore spaces. This is because the water in a given unit of the soil system tends to be at equilibrium or reach the same energy state. As this progresses, the problems of keeping an adequate supply of nutrients and of water entering the plant become increasingly complicated.

It is evident from figure 7.4 that as moisture is withdrawn from the soil and the thickness of the surface films of water on the soil particles is reduced, the plant root will be in contact with fewer soil particles and thereby greatly decrease its supply of nutrients as well as moisture. Although the moisture in the soil as well as the ions in the soil solution tend to adjust themselves to a state of equilibrium, the distance over which this adjustment is made is not great (16, 32, 46). Also, as the

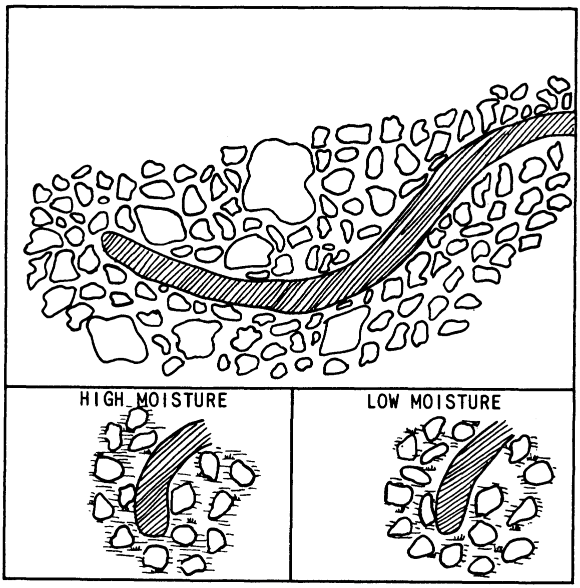

Fig. 7.4 — Plant root in contact with soil particles.

distance over which this adjustment is made is increased, the time for it to reach equilibrium is likewise increased. As the moisture decreases, the liquid surface contact between many soil particles is broken and the effective distance between them may be increased tenfold, even though they may be only a short distance apart in a linear sense.

It has been shown that when part of the roots of a plant are placed in dry soil, they will absorb nutrients (20, 21, 33, 55). However, it was also shown that the quantity of nutrients absorbed was small compared to the total supply needed for optimum plant growth. Plant roots, even in soils at 15 atmospheres tension, are in contact with many soil particles and may absorb nutrients, as well as small amounts of water, at this tension from a soil. Since the moisture film around the soil particles represents the zone of contact between plant roots and the soil particles, it is reasonable to assume that the number of soil particles that may be in contact with a plant root increases as the moisture tension decreases.

Perhaps one way to increase the probability of root contact with soil particles is to increase the bulk density of the soil. This is practiced to a certain extent. There are limits to which this may be done because too great an increase in bulk density results in a decrease in soil aeration. Unless the plant roots have an ample supply of oxygen, they will not absorb very much of anything. A good example of increasing soil density to benefit a crop is firm seedbeds. After the soil has been worked, it is usually loose and friable. After seeding, it is generally rolled or packed in some manner. This is to enable the roots of the young seedlings to come in contact with enough soil particles to survive during the period of germination when the soil moisture stress may be considerably below field capacity. Many a seeding has failed because of the lack of a firm seedbed.

When a soil is at field capacity and the ions in the soil solution are at equilibrium, there is a concentration, which may be designed as X, of these ions in the solution. As the soil becomes drier or as the moisture tension increases, there is an effective increase in the concentration of ions in the soil solution. If a soil contains 30 percent moisture at field capacity and 10 percent moisture at 15 atmospheres tension (wilting point), then the concentration of ions in the soil solution at 15 atmospheres tension will be 3X or 3 times as great as at field capacity (it being assumed that there was no net removal of ions from the soil solution).

As the concentration of ions in the soil solution increases, certain chemical reactions occur and some of the ions are precipitated, fixed, or absorbed on the surface of clay particles. Potassium may be fixed by 2-1 type clays (54, 59). Phosphorus may be precipitated (7, 49) or absorbed on the surface of clays (6). Boron may react with organic matter (36) or be precipitated as a borosilicate (18, 36). Calcium, magnesium, or iron may be precipitated if their concentrations are very high. Nitrates and chlorides are very soluble and generally remain in solution, often reaching very high concentrations.

Moisture Stress

Plants growing under conditions of moisture stress are generally high in nitrates, low in phosphate and potassium, and contain variable amounts of calcium, magnesium, and other elements (11, 12, 25, 28, 34, 37, 52, 53).

Why are plants grown under conditions of moisture stress high in nitrates? There are perhaps two basic reasons: (a) The concentration per unit of soil solution is much higher than when at field capacity. (b) The plant is unable to absorb enough phosphorus for rapid growth and, because of certain physiological processes, nitrogen accumulates in plants that are low in phosphate. It is, of course, recognized that the rate of plant growth is also a function of moisture stress.

Certain cases where phosphorus accumulates in plants under low moisture tension have been reported (25, 26, 33). In most cases, however, there is generally a lowering of the phosphorus content of plants growing under conditions of moisture stress (9, 11, 50, 51). It must be remembered in nitrogen and phosphorus nutrition of plants that phosphorus will accumulate in plants growing under nitrogen deficient conditions. Conversely, nitrogen will accumulate in plants growing under phosphorus deficient conditions. Therefore, it is entirely feasible for plants to accumulate phosphorus during periods of high moisture stress. Soils extremely high in phosphate, as the Maury soil, supply adequate phosphorus to plants during periods of moisture stress.

The low content of potassium in plants grown under conditions of moisture stress is best explained in terms of cation antagonism and plant root contact with fewer soil particles. The absorption of potassium by plants is inversely related to the calcium content of the soil. Increasing the soil moisture tension brings about an effective increase of both calcium and potassium in the soil solution. This increased concentration evidently depresses the absorption of potassium. The initial concentration of the two cations is important in determining this effect, and this varies quite widely in different soils. This perhaps accounts for the variation in results reported in the literature.

The concentrations of calcium, magnesium, and other elements vary quite widely in different soils. No general statements will be made at this time as to their behavior under periods of moisture stress. The initial concentration of these ions, as well as the concentrations of other ions, will determine their behavior under periods of moisture stress. The number of soil particles with which a root comes in contact will also affect the plant composition.

Root Activity and Penetration Under Variable Moisture Conditions

The moisture and fertility factors determine to a great extent the plant root ramification of a soil. Jordan, Laird, and Ferguson (27) found that corn plants fertilized with nitrogen during a dry year depleted the soil moisture to a depth of three feet. The unfertilized plots contained available moisture in the top three feet of soil. Painter and

Leamer (35) reported that the roots of grain sorghum removed moisture to a depth of at least 57 inches on plots where a moisture tension of 0.7 atmospheres or below was maintained at a nine-inch depth. On plots where the tensions were allowed to reach 12-15 atmospheres at nine inches before irrigation, moisture was removed to an approximate depth of 45 inches, with the greatest removal above 21 inches.

Hobbs (17) found that alfalfa utilized subsoil moisture reserves rather completely to a depth of eighteen feet in four years. Moisture reserves under fertilized stands of alfalfa were reduced to a lower level than those under unfertilized alfalfa stands. A shallow-rooted crop, bromegrass, did not seriously deplete the soil moisture below four feet. Soil moisture extraction data by Hagan and Peterson (13) indicate that, if the botanical composition remains nearly constant, there is no material effect on the distribution of absorbing roots in Ladino clover-grass and broadleaf trefoil-grass mixtures. Moisture extraction under clover-grass mixtures was largely confined to the top four feet of soil, while under the trefoil-grass appreciable extraction occurred throughout six feet of soil. Because of differences in effective depth of rooting, moisture extraction in the surface three feet of soil was most rapid under Ladino clover mixtures, less rapid under trefoil-grass, and slowest under alfalfa-grass. Land and Carreker (29a) measured the distribution of roots under corn and cotton and found that few roots of either crop penetrated below eighteen inches under either irrigated or unirrigated conditions. The proportion of feed roots of cotton in the top six inches was 55 percent with irrigation and 73 percent without irrigation. Approximately 85 percent of the corn roots were in the top six inches of soil.

The effective rooting depth may be defined as the depth to which a soil continues to lose moisture during a prolonged period of rainless weather (5, 39). Carey and Blake (5) reported that the effective rooting depth of sweet corn varied with soil type from 11 to 35 inches. When differences in rooting depth were combined with moisture per unit depth, tomatoes had about 4 times as much water at their disposal in a Sassafras loam as in a Nixon loam. Wheat had less than half as much as tomatoes when both were growing on a Sassafras loam.

Many factors may operate singly or in combination to determine the amount of water utilized by plants. The effects of these factors may not necessarily be constant from year to year as many of the factors are dependent upon the intensity or level of the other factors.

Fertilization of Farm Crops Under Variable Moisture Conditions

The effect of moisture tension on root ramification in a soil is quite evident. An intensive root system will enable the plant to exploit more extensively the native soil fertility and utilize more efficiently the nutrients added as fertilizers.

The stage of physiological development has a great deal to do with the results obtained from subjecting plants to periods of moisture stress

(15, 19, 22, 42, 48, 58). Generally the critical period is during the reproductive cycle of the plants involved. This is well illustrated by figure 7.5.

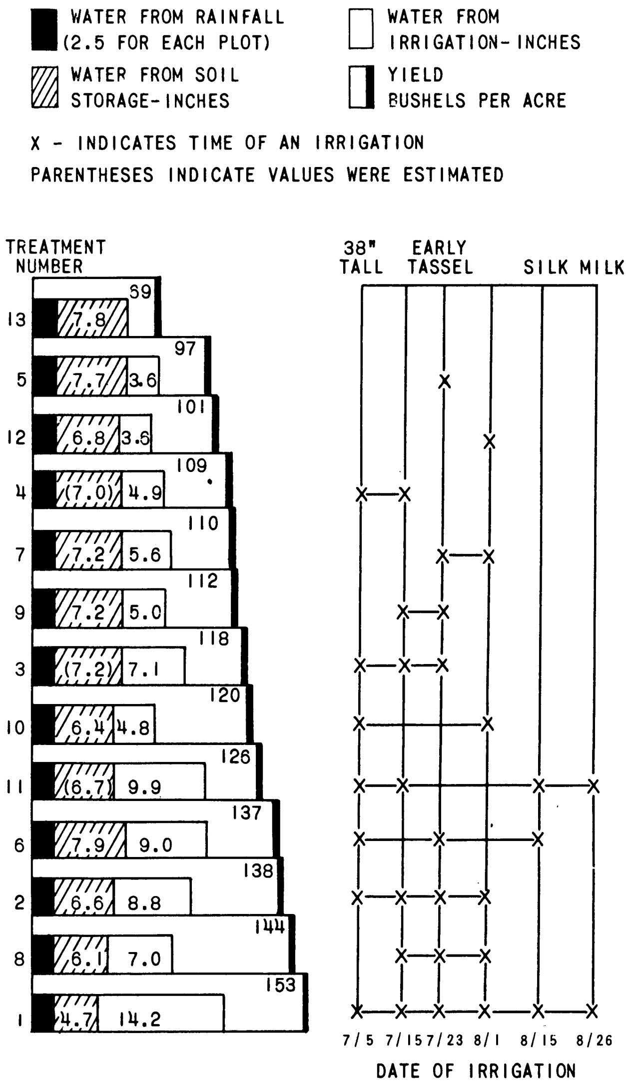

Fig. 7.5 — Yield of grain and water use by corn with different irrigation treatments. L. S. D. (5% level) for yield = 21 bu./acre. Howe and Rhoades (19).

Botanical Composition

As fertility and moisture treatments influence the physiological development of plants, it is reasonable to expect that they will affect the botanical composition of certain forage crop mixtures. Figure 7.6 shows the effect of different treatments on the percentage of clover and grasses in a meadow.

Both fertilizer and moisture treatments had an effect on reducing the amount of clover in the meadow. This change in vegetative

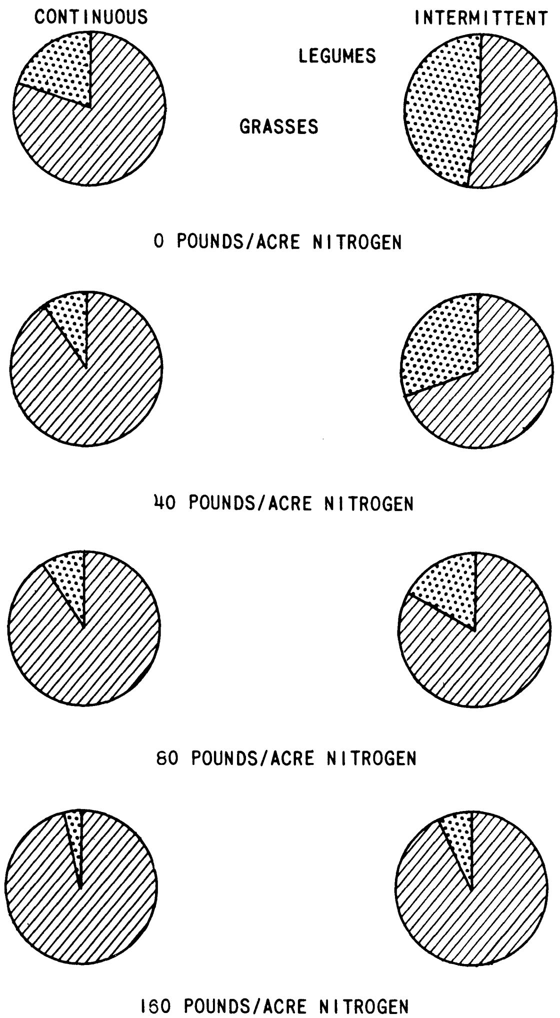

Fig. 7.6 — Effect of nitrogen and moisture variables on the composition of a meadow. Rouse (43).

composition of the meadow probably alters its nutrient value as a feed, as well as its nutrient and moisture requirement. As pointed out by Hagan and Peterson (13), the moisture requirement for an irrigation schedule must be based upon the moisture conditions within the root zone of the shallowest rooted component to be maintained in a forage mixture. With this difference evidenced in the rooting systems of forage mixtures, it is evident that the relative response of different species within a mixture to a given fertilizer treatment is quite different. In this particular case, a nitrogen-moisture variable was used, and this treatment combination favored the grasses in the forage mixture more than the legumes. Consequently, there was a net decrease in the percentage of legume composition. If the two extremes of the treatment combinations are taken as examples, the result is a comparison of a forage mixture of almost 50 percent clovers to one of less than 1 percent clovers. Since the primary objective of producing forages is to supply a feed for animals, the question immediately arises as to whether or not the two forages had equal feeding values and produced the same TDN per acre.

Chemical Behavior of Soil Elements

The chemical behavior of different fertilizer elements in a soil also enters into the magnitude of the response to a given level of that element under different degrees of moisture stress. This relationship, along with the different rooting characteristics and nutrient requirements of the various species of forage mixtures, enters into the results obtained from fertility-moisture variables.

Moisture Stress and Growth

The effect of moisture stress upon the growth of plants has been illustrated by the work of Wadleigh and Gauch (57).

They measured the length of cotton leaves daily and compared the rate of leaf growth to the intensity of the soil moisture stress. As is evidenced in figure 7.7, the rate of leaf elongation starts to decrease when the soil moisture tension reaches 9 atmospheres, and it is almost zero when the tension reaches 15 atmospheres. Under the conditions of this experiment, leaf elongation was expressed as a second degree function of the soil moisture stress for a given irrigation cycle.

The level of soil moisture which should be maintained for optimum growth of plants has been the objective of many irrigation experiments. It is recognized that it is physically impossible to maintain soil moisture in a soil of actively growing plants at a given tension. Therefore, the maintenance of a minimum soil moisture tension in a given zone of soil is the approach generally taken. In some cases the integrated soil moisture stress over the entire root zone is used (49a). Either approach provides a means for maintaining a minimum soil moisture level and thereby provides information on the moisture requirements for maximum growth of a crop under a given set of soil conditions. In some

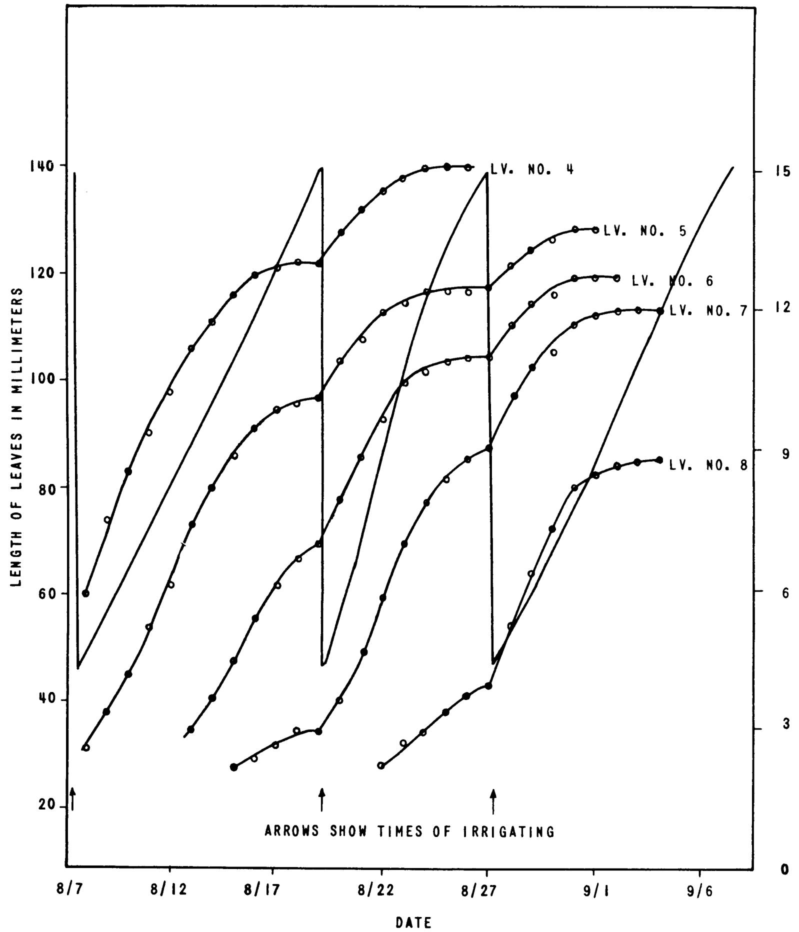

Fig. 7.7 — Effect of moisture tension on leaf elongation. Wadleigh and Gauch (56).

instances the "percent available moisture" level is used to determine moisture requirement and irrigation schedule. However, due to the different moisture-holding properties of soils, the relative energy by which moisture is held by soils is quite different. A sandy soil has lost over 90 percent of its available moisture at 1 atmosphere tension (see figure 7.2), while heavier textured soils do not lose this percent of available moisture until they reach a much higher tension.

Perhaps the fertilizer element that gives the greatest positive interaction when combined with moisture is nitrogen. This element is most often combined with moisture variables in the experimental results reported to date. Results shown in figure 7.8, by Painter and Leamer (35),

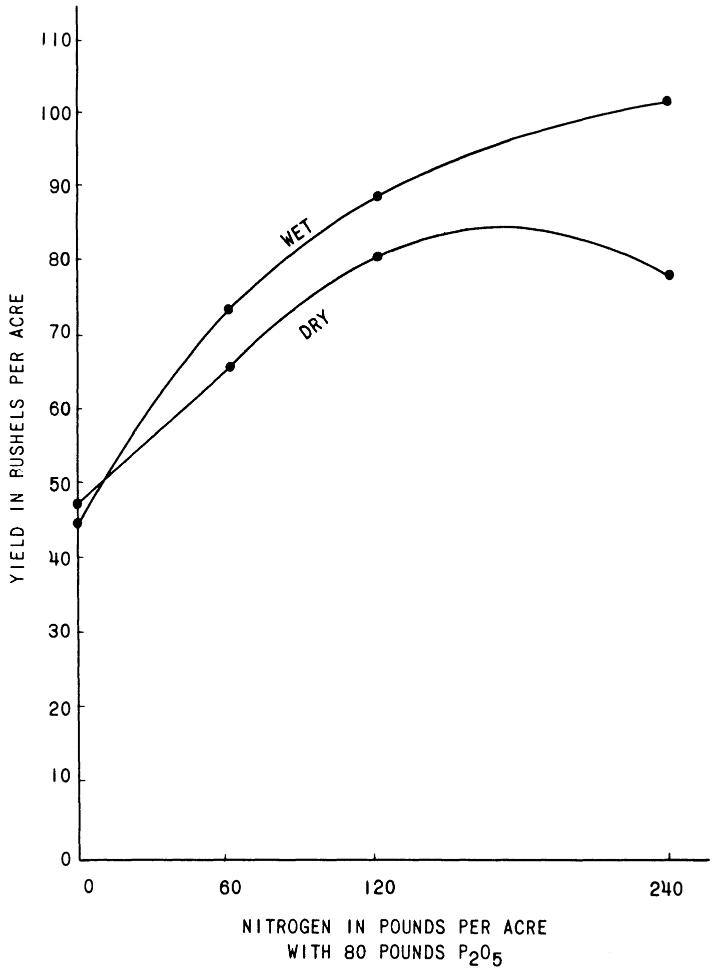

Fig. 7.8. — Effects of nitrogen and moisture on the yield of grain sorghum. Painter and Leamer (35).

represent the data obtained in corn experiments where nitrogen and moisture were varied. In the "wet" treatment, which was 0.7 atmospheres tension at 9 inches depth, the slope of the response curve obtained never reached zero. In the "dry" treatment, which was 12-15 atmospheres at 9 inches depth, the maximum yield was obtained at 120 lbs. N/A. A higher rate of N at this moisture level resulted in a slight decrease in yield.

Paschal and Evans (37) combined moisture, nitrogen, and spacing variables in an experiment with grain sorghums. They found that, as the moisture and nitrogen levels were increased, a greater yield was obtained by increasing the plant population. In this particular case the plant population was doubled. This brings out another problem in moisture fertility experiments, which is the desired plant population necessary to give an accurate measure of the treatment potential. In this particular case the yield obtained by M_1S_2 (moisture tension<0.7 atmospheres at 9 inches depth and 20,028 PPA) was quite different from that obtained by M_1S_1 (moisture tension<0.7 atmospheres at 9 inches depth and 43,560 PPA) at the higher nitrogen levels. The M_2 (<12-15 atmospheres at 9 inches depth until heading, then the same as M_1) moisture treatment indicates that grain sorghums are not as responsive as corn when moisture stress is reduced during the reproductive stages.

Once the response curve has been established, the point on the curve for the most economic yield may vary as prices fluctuate. However, the production surface should remain fairly constant for the conditions under which it was obtained.

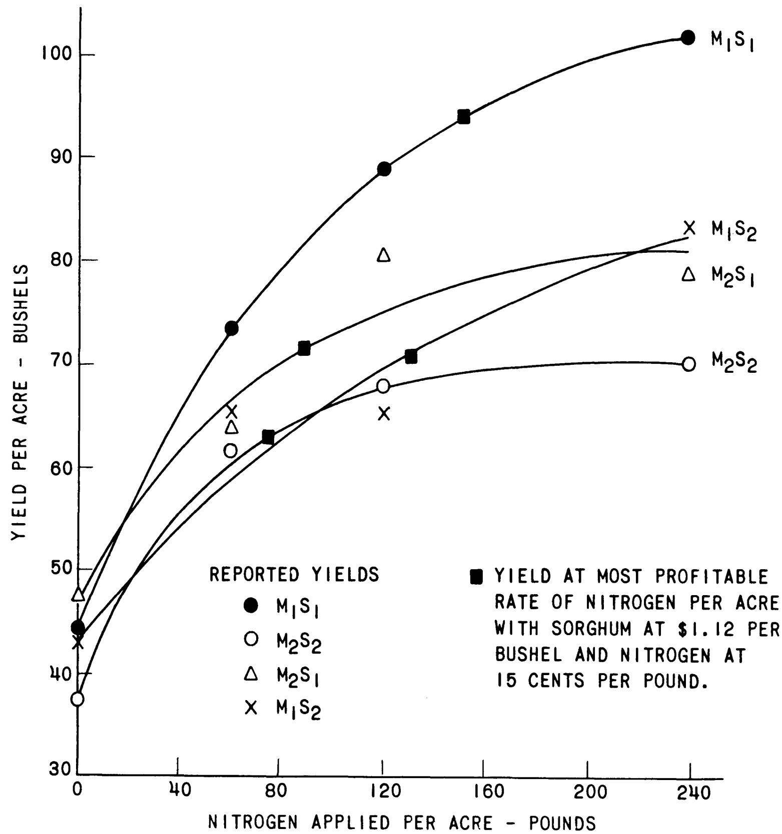

Fig. 7.9 — Effect of nitrogen, moisture, and spacing on the yield of grain sorghum. Paschal and Evans (37).

Fisher and Caldwell (10) of Texas have reported some interesting results from the application of nitrogen to Coastal Bermuda-grass under conditions of heavy irrigation. Increases in yield of dry forage were obtained from each increment of nitrogen up to 800 lbs. N/A (5 separate applications). Of particular importance is the rapid decrease in the amount of water needed to produce a ton of forage as the level of nitrogen is increased. This is of great importance in the efficient use of water for supplemental irrigation in the humid region.

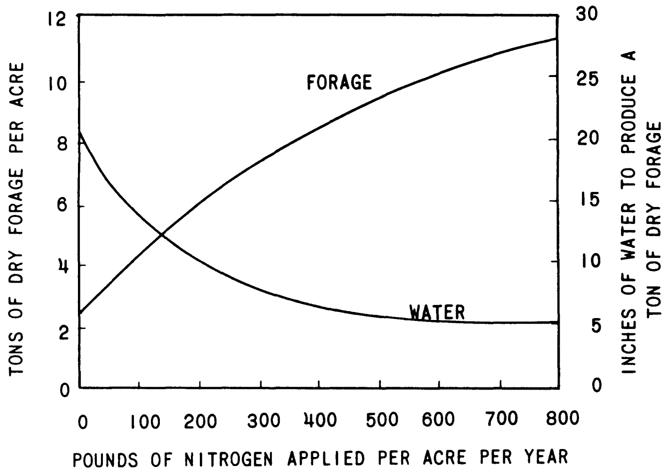

Fig. 7.10 — The effect of nitrogen on forage yield and water utilization of Coastal Bermuda grass. Texas A & M Progress Report 1731.

Experimental Designs for Combined Moisture and Fertility Experiments

In the study of variable moisture levels for crop production there are two primary objectives: (a) Determine the minimum moisture tension for maximum yield. (b) Determine the fertility requirement for this moisture level. In many instances, these two objectives are combined in the same experiment. Such a combination works very well in certain experimental designs, but the area involved often gets very large if many levels of each variable are studied.

Irrigated plots must be large because of moisture movement in a soil, problems of application, and lateral root extension by plants. It is possible to have fertility plots that are much smaller and still have a reliable measure of the treatments under study. A split-plot experimental design fits this combination of variables and has been found to work very well in experiments conducted to date.

There are several factors that may affect the fertility level desired for optimum yield when the moisture regime of the crop is controlled.

Some of these factors tend to counterbalance others, but considerably more information is needed to determine where the equilibrium point lies. One school of thought is that, with an ample supply of available moisture, larger and more rapid plant growth will result, bringing about a need for a greater supply of plant nutrients. On the other side, tending to counteract this increased nutrient requirement, there is a more extensive root system. This enables the plant to feed from a larger volume of soil and results in an increased efficiency in use of nutrients in the soil and of those added as fertilizers. There is a great need for information that will evaluate these counteracting factors.

In most experiments involving the production of farm crops, an effort is made to obtain the maximum yield from a specific element under a given set of conditions. It is recognized that this maximum yield may not be the most economical yield; but once the response curve has been established, the point for the most economical yield may very well move up or down the curve from year to year.

There are many variables which, when combined, give a significant interaction. Also, when a number of factors are involved, the same product may be obtained by altering the levels of the different factors. During periods of price change, it may be desirable to alter the level of the various factors to obtain the desired yield in the most economical way.

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