CONFIRMATION OF THE NUTRIENT MOBILITY CONCEPT OF SOIL-PLANT RELATIONSHIPS

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In an earlier paper (6), it was pointed out that the nutrient requirements of crops are determined to a great extent by the mobility in the soil of the available soil forms of the nutrients.

The concept was stated (6, p. 19) as follows: "As the mobility of a nutrient in the soil decreases, the amount of that nutrient needed in the soil to produce a maximum yield (the soil nutrient requirement) increases from a variable 'net' value, determined principally by the magnitude of the yield and the optimum percentage composition of the crop, to an amount whose value tends to be a constant. The magnitude of this constant is independent of the magnitude of the yield of the crop, provided the kind of plant, planting pattern and rate, and fertility pattern remain constant, and provided relatively similar soil and seasonal conditions prevail."

At one end of the mobility scale are the relatively immobile nutrient forms, such as the sorbed form of phosphorus and the exchangeable forms of potassium, calcium, and magnesium. Under the usual conditions existing in well-drained silt and clay loam soils, these available forms have little mobility. In effect, plant roots have to explore for them. The highly developed root-hair system of plants may have resulted from the need for an intensive feeding mechanism for these relatively immobile soil forms. In contrast, water plants have very simple root systems.

Because of the low mobility of the sorbed and exchangeable soil forms, a plant "feeds" from them in proportion to the size of its root and root-hair system, which is in proportion to the size of the plant. The level of a nutrient just adequate for the smaller yields obtainable in unfavorable seasons will, therefore, be equally adequate for the larger yields obtainable in more favorable seasons. The larger root system, with its larger numbers of root hairs, contacts proportionately more of the relatively immobile available forms. When there is an even distribution of sorbed phosphorus or exchangeable potassium in adequate amounts in the soil, each root hair obtains relatively the same amount of these nutrients. When seasonal conditions are unfavorable, plant growth will be restricted, but the sufficiency of a relatively immobile nutrient remains the same. The smaller plants still obtain adequate amounts and their composition is the same as that of the larger plants growing in a more favorable season.

Differences in planting pattern and/or planting rate require different levels of the relatively immobile nutrient forms. As the rate of planting is increased the number of root systems increase and competition between roots is intensified. The nutrient level adequate for the lower rate of planting is now inadequate for the higher rate of planting. The root hairs from roots of adjoining plants are now providing increased competition between plants for the nutrients. For example, with two corn plants in a hill the competition is less than with four plants in the hill. It follows that the sufficiency for yield of any given level of a nutrient is less with four competing corn plants, and that the nutrient requirements increase as the rate of planting increases. This means that the sufficiency for yield of the available soil form decreases as root systems of adjoining plants compete more strongly with each other.

Different kinds of plants, such as corn and wheat, have different rooting habits, and therefore differ in their ability to obtain the relatively immobile nutrient forms. Different kinds of plants also differ in composition at optimum yield, and the levels of the relatively immobile nutrients needed for optimum yield are, therefore, not directly related to size of yield, but are determined by (*a*) the kind of plant, (*b*) the planting pattern and rate of planting, (*c*) the form of the nutrient, and (*d*) the distribution of the nutrient in the soil in relation to the planting pattern.

A single plant growing in a very small pot requires a higher level of the relatively immobile forms than when growing in a field where its roots have an unlimited feeding area. The levels of sorbed phosphorus and exchangeable potassium must be higher in the pot because the plant's root hairs are now competing with each other. Pot experiments are, therefore, valueless for establishing fertilizer requirements for field-grown crops, since they do not represent field conditions.

In the yield equation involving only the soil form of a nutrient, as represented by b in the equation

$$\log (A - y_o) = \log A - c_1 b \qquad [1]$$

the term c_1 represents the efficiency of b for yield when b represents the amount of a relatively immobile but available soil form, as can be expressed by a soil test value. Examples are the sorbed form of phosphorus and the exchangeable forms of potassium, calcium, and magnesium. The c_1 value for a certain crop will vary with the kind of nutrient and with the form and distribution pattern of that nutrient in relation to the planting pattern and rate of planting of the crop.

When a fertilizer is applied, the equation is changed to include x, the fertilizer form, becoming

$$\log (A - y) = \log A - c_1 b - cx \qquad [2]$$

with c representing the efficiency of x, the fertilizer form. Here the value of c for x involves both the chemical nature of x and its distribution pattern in the soil in relation to the planting pattern. The value of b, as used here, is in terms of pounds of the available soil form in 2 million pounds of soil (pounds per acre) when b is in terms of K or P; also, x is in terms of pounds per acre of K_2O or P_2O_5.

For example, b can be represented by the P_1 soil test value in terms of pounds of sorbed phosphorus per 2 million pounds of soil (pounds per acre), and x can represent the pounds per acre of P_2O_5 applied as a soluble fertilizer, in a given distribution pattern relative to the planting pattern. The method of applying the fertilizer may be drilling in the row with the seed, broadcasting and disking, placing in the hill, or any similar method.

Once the c_1 and c values for b and x, respectively, have been determined for a given crop, planted at a certain rate and in a certain pattern, the fertilizer requirement for each soil test value can be calculated for any desired approach to the 100 per cent yield level, provided the soil test used to measure b is the same as that used for the original correlation.

According to the mobility concept, it is because exchangeable potassium and the sorbed form of phosphorus are relatively immobile soil forms that they follow the Mitscherlich-Baule percentage sufficiency concept (2).

Because nitrate nitrogen is relatively mobile in the soil, it is highly available. The net nitrogen needs, exclusive of leaching or other losses, are determined, therefore, by the size of the crop and its nitrogen composition at optimum yield, that is by the nitrogen content. Because of this, nitrate nitrogen follows Liebig's law of the limiting nutrient (11).

For example, a 100-bushel corn yield contains, at maturity, around 150 pounds of nitrogen; the net nitrogen needs, exclusive of leaching or other losses or gains are, therefore, around 150 pounds of nitrogen per acre. As the yield possibility A varies with the favorableness of the soil and the season, or with the rate of planting, so will the nitrogen requirements vary. In corn belt soils, nitrogen is seldom deficient for the first stages of growth, and nitrogen deficiencies are rare in knee-high corn. A test of the leaf will generally give a positive nitrate test value. But as the corn grows, the tissue test value decreases on nitrogen-deficient soils, and a negative test is soon obtained. Typical nitrogen-deficiency symptoms follow and the yield will be reduced in proportion to the nitrogen deficiency. A potentially deficient level of nitrogen can be more than adequate during the first stages of growth, but will become deficient in the later stages of growth. The yield will be restricted in proportion to the nitrogen deficiency. Thus a crop's net nitrogen needs are directly related to the size and nitrogen composition of the crop, because nitrate nitrogen is following Liebig's law of the limiting nutrient. One amount of nitrate nitrogen can be adequate for only one yield of a given size and composition (11).

In contrast, when either phosphorus or potassium is inadequate, yield is restricted during all stages of growth; and, at all stages, as the yield varies with soil and season, the composition of the plant will be a deficient one.

Variations in method of application also vary the requirements for the relatively immobile nutrient forms, since the application pattern influences the availability of these forms for plant uptake.

Experiments have shown that when wheat is planted in 8-inch rows, at the rate of 90 pounds of seed per acre, and P_2O_5 is broadcast and disked ahead of planting, the yield equation becomes

$$\log(A - y) = \log A - 0.0184b - 0.25\log x \qquad [3]$$

Here b is the P_1 soil test value in pounds of phosphorus per 2 million pounds of soil when the native phosphorus is rather evenly distributed in the soil, and x represents the pounds per acre of P_2O_5, applied in a broadcast and double-disked pattern ahead of planting. The values of A and y can be expressed either as percentage yield values or in terms of bushels of wheat per acre (7). In all the equations given in this paper, the value of b is in terms of P or K as pounds per 2 million pounds of soil, and x is in terms of K_2O or P_2O_5, also as pounds per 2 million pounds of soil.

These c_1 and c values for wheat, when the phosphate was broadcast, were found to hold equally well the following season, although the yields for all rates, on all four fields included in the study, were almost 50 per cent higher than in the previous year. However, the c_1 and c values, and hence the percentage sufficiency values, remained the same for both years.[1]

Neither did the variations in soil type and season that occur along a 200-mile north-south line in Illinois from Dixon Springs to Urbana vary the c values for the four fields. When soils vary widely in chemical properties, changes in c_1 and c can be expected.

In the case of P_2O_5 for wheat, the 0.25 log x form of the equation means that c for x varies with the rate of application when x is broadcast and disked. A value of 0.0088 for c for x is an equivalent value for the cx term, but is not as precise as the 0.25 log term.

The phosphorus composition of the wheat grain in the above study varied with the rate of application when the P_2O_5 was broadcast and disked, giving the composition equation

$$\log(0.583 - y) = \log 0.583 - 0.0143b - 0.00117x \qquad [4]$$

where 0.583 is A and represents the maximum phosphorus composition of the grain (1).

In contrast, when P_2O_5 was drilled in the row with the wheat, the phosphorus composition of the grain on all the treated plots was the same as on the check plots, that is there was no change in composition with rate (18).

The yield equation for P_2O_5 drilled in the row with the wheat grain is

$$\log(A - y) = \log A - 0.0184b - 0.0178x \qquad [5]$$

which is a much higher efficiency of x for yield than for the broadcast method.

A study of the response of corn to potassium when corn was planted four kernels to the hill and phosphorus was broadcast and disked in ahead of planting,[2] gave the equation

$$\log(A - y) = \log A - 0.0054b - 0.0086x \qquad [6]$$

when b is the exchangeable potassium in an air-dried sample in terms of pounds of K in 2 million pounds of soil, and x is in terms of K_2O per acre, broadcast and disked. Another part of the same study gave the equation

$$\log(A - y) = \log A - 0.051b - 0.02\,P_2O_5 \qquad [7]$$

for P_2O_5 when broadcast and disked ahead of planting.

For the same planting pattern, when the P_2O_5 is placed on two sides of the hill, 1½ inches away from and 1 inch below the seeds, using 4 seeds to the hill, the equation is

$$\log(A - y) = \log A - 0.051b - 0.032\,P_2O_5 \qquad [8]$$

The value of 0.032 is based on the studies of Webb and Pesek using their data from non-calcareous soils (19). The Iowa group have also studied the residual effects of this method of application (9).

Tentative c values for soybeans[3] planted in 40-inch rows are

$$\log(A - y) = \log A - 0.05b - 0.01\,P_2O_5 \qquad [9]$$

when the P_2O_5 is broadcast, disked, and plowed under, using a seeding rate of one bushel per acre in 40-inch rows. The low value of 0.01 for P_2O_5 is due in great part to the method of application, which involves much more mixing

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[1] Unpublished data, 1955.

[2] J. A. Eck, unpublished M.S. thesis, 1958.

[3] L. T. Kurtz, unpublished data, 1959.

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The P_1 soil test does not extract the total amount of the sorbed phosphorus; it is, rather, a "measure of" the total amount, in that it extracts a proportionate part of the total. In contrast, the concentrated sodium acetate solution suggested by the writer in 1932 extracts practically the total exchangeable potassium from an air-dried sample (4).

Recent data by Hassan,[4] involving a study of the P_1 test and the response of corn to residual rock phosphate applications of 4 tons on the Illinois experiment fields, show that neither the native apatite forms nor the rock phosphate added have any direct effect upon yield. Where rock phosphate had been applied, the small increase in yield obtained was directly related to a slightly higher level of the sorbed form of phosphorus on the rock-phosphated plots, as measured by the P_1 test. The 4 tons of rock phosphate added have left the soil almost as deficient in phosphorus as the plots receiving no phosphorus. The initial response to rock phosphate sometimes observed is probably due to a small amount of soluble forms present in the rock phosphate when first applied.

It is now recognized that the Illinois P_2 test (5), which extracts both the sorbed and apatite forms of phosphorus, has no place in a soil-testing program, because the native apatite and rock phosphate forms are not available for crop growth. The "Universal" soil extracting solution (14) based on the writer's 1932 potassium test (4) also dissolves the unavailable apatite forms, but it does not effectively remove the available sorbed phosphorus, and is, therefore, valueless as a test for available phosphorus. The same is true of Truog's soil test for available phosphorus (17) and the writer's first phosphorus test (3). In contrast, the soil test suggested by Dyer in 1894, is satisfactory for soil phosphorus, because citric acid extracts only the sorbed phosphorus, not the unavailable apatite forms (8).

The soil test correlations described above are based on tests which measure, or are a measure of, the total amount of the available soil form of a nutrient. The idea that a soil test should measure the availability of a soil nutrient form, as suggested by Peach (16) and Hibbard (10), is untenable, because each nutrient form has a different efficiency for each different kind of crop, each planting pattern, and each planting rate.

It is only when a test measures either the total amount or a proportionate part of a relatively immobile available soil form of a nutrient that it is possible to correlate the test value with the efficiency of the soil and fertilizer forms through the Mitscherlich-Baule percentage sufficiency concept as limited by the nutrient mobility concept.

The nutrient mobility concept serves to restrict the law of the limiting nutrient and the percentage sufficiency concept to those situations where they apply. This makes it possible to plan experiments which recognize the role played by each nutrient form in soil-plant relationships, especially those experiments designed for soil-test correlations which measure the efficiency of the soil and fertilizer forms for each crop.

That nitrogen follows Liebig's law of the limiting nutrient is illustrated by the well-known and accepted fact that a given level of nitrate nitrogen can be more than adequate for the first stages of growth, yet can become highly deficient in the later stages of growth, thus limiting yield to a certain number of tons or bushels of a nitrogen-deficient crop. In contrast, a certain level of sorbed phosphorus or exchangeable potassium, having a given distribution pattern in the soil, will have the same percentage sufficiency for yield, as the yield varies widely with the soil and season, provided the kind of crop and its planting pattern and rate remain constant.

The constancy of c_1 and c for the soil and fertilizer forms, as yields vary widely with the soil and season, confirms the role they play as nutrients following the Mitscherlich-Baule percentage sufficiency concept (12, 13).

Liebig recognized that the soil nutrients could exist in relatively immobile forms and that "roots extract nutrients from those portions of the soil, penetrated with water, which are in direct contact with their absorbent surfaces" (11). Liebig did not, however, recognize that such sorbed forms would not follow his law of the limiting nutrient.

The rather simple role of the nitrate form of nitrogen as a limiting nutrient has now been generally recognized and accepted, and nitrogen recommendations are based principally on an

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[4] Hassan, unpublished Ph.D. thesis, University of Illinois, 1961.

estimate of the probable yield and nitrogen composition of the mature crop.

But the role of phosphorus, potassium, and other exchangeable or sorbed nutrients as relatively immobile soil forms, following the percentage sufficiency concept, has been generally overlooked. Very few field studies leading to correlations of soil forms with fertilizer requirements, through soil tests and the percentage sufficiency concept, have been reported. F. van der Paauw, who has also applied the percentage sufficiency concept to soil fertility studies through the yield equation, is one of the few who recognize that c_1 and c can vary as other factors vary (15).

The failure of those interested in fertilizer requirements to successfully apply the Mitscherlich-Baule percentage sufficiency concept to their results may be due in part to the fact that nitrogen was originally believed to follow the percentage sufficiency concept, making it impossible to demonstrate the concept when nitrogen was deficient.

Given the c_1 values for exchangeable potassium and sorbed phosphorus and the soil test values for each, when b is in terms of pounds of P and K per acre 2 million pounds of soil, as measured by the soil tests for these nutrient forms, it becomes possible to illustrate the percentage sufficiency concept. According to the percentage sufficiency concept, as modified by the nutrient mobility concept, the percentage sufficiencies of phosphorus and potassium for yield can be measured only when nitrogen is adequate, since it acts as a limiting nutrient. If phosphorus is 90 per cent sufficient for a certain crop planted at a certain rate and in a certain pattern, and potassium is 80 per cent sufficient, then 80 per cent of a 90 per cent yield will be obtained, or 72 per cent of A, the yield possibility, as it varies from season to season. The percentage sufficiency concept is illustrated in table 1 by the data of Hassan, mentioned above, who calculated the A values from the b, c_1, and yo values in the equation

$$\log (A - yo) = \log A - c_1 b$$

where b is the soil test value for either phosphorus or potassium and c_1 is the corresponding efficiency factor for the soil test value. In this case, yo is the yield of corn while b is the soil test value for either the P_1 test or the test for exchangeable potassium.

TABLE 1

Calculated percentage sufficiencies and A values for corn (Enfield, 1944–1947 rotation period) and wheat (Carthage field, 1956)

Treatment	P_1	Exchang. K	Yield	Sufficiency			Yield Possibility (A)
				P	K	Px K	
	lb. P/A.	*lb. K/A.*	*bu./A.*	%			*bu./A.*
Corn (Enfield field, 1944–1947)							
RL	14.0	116	36.4	79	75	59	61
RLrP	17.2	123	38.7	87	76	66	59
RLrPK	19.0	268	52.2	88	96	84	62
Wheat (Carthage field, 1956)							
RL	17	208	26.3	51.3	95.6	49.0	54
RLrP	21	200	30.3	58.9	95.0	55.9	54
RLrPK	18	282	28.0	53.4	98.5	52.5	53

c_1 for exchangeable K = 0.0054
c_1 for the P_1 test value = 0.051

The data illustrated that, when the c_1 value for corn for exchangeable potassium and for the sorbed form of phosphorus are known, it is possible to calculate the percentage sufficiency of each nutrient, and, hence, the A value for each treatment, from the soil test value. The product of their percentage sufficiencies is the percentage of A obtainable, when both remain deficient, making it possible to calculate A from the yields obtained.

The data for corn, wheat, and soybeans from 18 experiment fields in Illinois over two different 4-year periods were analyzed by Hassan, with results confirming the c_1 and c values for the P_1 and exchangeable potassium tests as applied through the Mitscherlich-Baule percentage sufficiency concept. The data serve to confirm the percentage sufficiency concept, as limited by the nutrient mobility concept. They also demonstrate that applied rock phosphate and native apatite forms, have, as such, no availability for plant growth. The small increases in yield, where 4 tons of rock phosphate were applied, are associated with an increase of 2 or 3 pounds in the P_1 test value, leaving the soil almost as deficient as the untreated plots. The data also serve to illustrate the ineffectiveness of the native apatite forms, and they emphasize the fact that soil tests, such as the Universal

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The correlations reported in this paper illustrate that fertility requirements for the relatively immobile soil forms are unrelated to size of yield. Variations in the physical favorableness of the soil and the favorableness of the season can vary yields widely without changing the requirements for phosphorus and potassium. In contrast, the net nitrogen needs are directly related to size of yield and the nitrogen composition and vary widely as yields vary.

SUMMARY

Evidence has been presented which confirms the role of the relatively immobile soil forms of the nutrients as forms which follow the Mitscherlich-Baule percentage sufficiency concept. This evidence is in the form of field studies which show that the soluble fertilizer forms added, and the available soil forms already present, give yield responses which are independent of size of yield obtained, but depend on the kind of crop, the planting pattern and rate of planting, the form of the nutrient, and the distribution pattern of the nutrient relative to the planting pattern.

This is illustrated by field studies with phosphorus and potassium involving different crops, planting patterns and rates of planting, and different distribution patterns of the nutrient forms in the soil in relation to the planting pattern. The c_1 and c values which have been obtained remain constant as yields vary with the favorableness of the soil and the season. But the c_1 and c values vary widely with the kind of crop, planting pattern and rate of planting, and with the form of nutrient and distribution pattern of the nutrient in the soil in relation to the planting pattern.

In contrast, the nitrate form of nitrogen, acting as a relatively mobile nutrient form, is so highly available that the amount required, exclusive of leaching or other losses or gains, is no greater than the crop content at optimum yield. Hence nitrate nitrogen follows Liebig's law of the limiting nutrient.

This establishment of the validity of the Mitscherlich-Baule percentage sufficiency concept and of Liebig's law of the limiting nutrient confirms the nutrient mobility concept of soil-plant relationships.

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Boltzmann equation means
equality of electrochemical

$$\exp\frac{a}{2} = \frac{\sqrt{\quad}}{\quad}$$

phases, in which one of th
terms is zero.

It is easily seen that fo
such as clays, a negative
takes place. It is visualized
anion concentration betwe
equilibrium solution, the
being found in the suspens
properties of the colloid,
tential ψ_0, or electrical supe
σ, may be deduced from
measurements.

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[1] Station Centrale d'Ag
France.

[2] G. H. Bolt, Ph.D. thesis
1954.