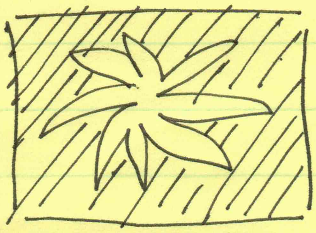
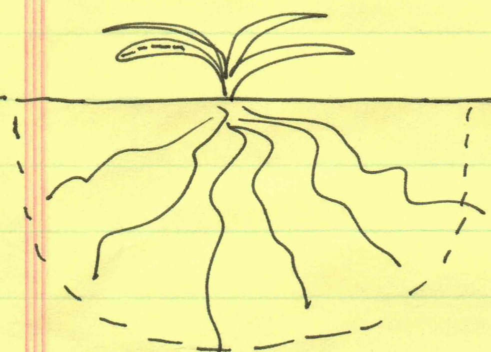
TOP VIEW

DEPENDS ON GROWTH STAGE

BIOMASS ≅ % coverage
COLOR ≅ concentration





root system
sorption zone

MOBILE NUTRIENTS

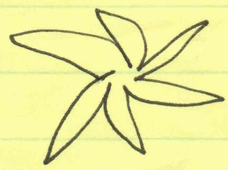
dependent on environment

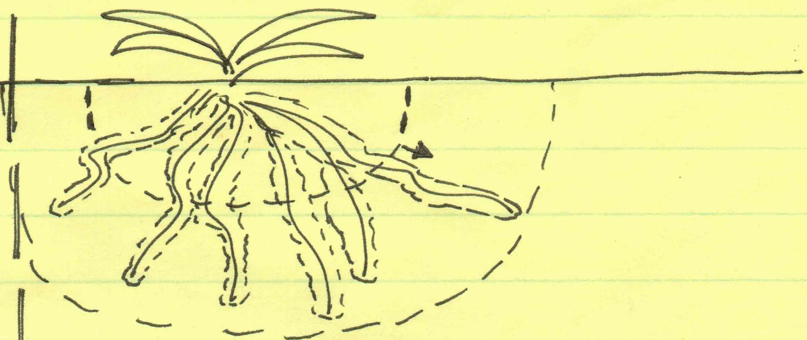
response depends on
reservoir

INDEPENDENT OF GROWTH STAGE

TOTAL → HNO_3-$HClO_4$ acid digest

NEED (P) CONCENTRATION
* PO_4-P → (acetic acid extractable)





root surface
sorption zone

IMMOBILE NUTRIENTS

independent of environment

response does not depend
on reservoir

A NUTRIENT MOBILITY CONCEPT OF SOIL-PLANT RELATIONSHIPS

ROGER H. BRAY

Illinois Agricultural Experiment Station

Received for publication May 24, 1953

Ever since Liebig stated the mineral theory of plant nutrition, scientists have been interested in the essentiality of the elements, the nature of their available forms in soil, and the relationships between the amounts of these available forms and plant growth. Scientific control of soil fertility depends on this knowledge.

Liebig's law of the minimum was one of the first attempts at formulating a concept to explain the nature of soil fertility (9, p. 105). The law stated that the nutrient present in least relative amount is the limiting nutrient. It implied that all the other nutrients were present in excess until the deficient or limiting nutrient was made adequate, whereupon the one present in the next least relative amount became the deficient nutrient, and so on. Because it was easily understood and appeared logical, the law was readily accepted and is used very generally to illustrate the nature of soil fertility. For example, if a soil contained enough nitrogen for 50 bushels of corn per acre, enough phosphorus for 60 bushels, and enough potassium and other nutrients for 70 bushels or more, 50 bushels of corn is all that could be produced and nitrogen would be the "limiting" nutrient.

Thus Liebig's law of the minimum could be interpreted as meaning that the crop used up all of the deficient nutrient in the soil, making the yield directly proportional to the amount of the deficient nutrient present and the crop content of the nutrient.

The first attempts to measure the fertility of a soil by chemical methods were, therefore, based on the idea that the chemical method should simulate plant feeding and should remove amounts similar to crop content. Dyer's citric acid method for measuring the available nutrients was based on this principle.

For years, during and after the time of Liebig, agriculturists believed that the fertility in a soil any one year depended on the amounts of nutrients which became available through weathering during the year. They had little conception of the immense amounts of most of the nutrients that most soils can accumulate and hold in forms which, while available for plant feeding, are not easily leached out by rainfall.

A second major concept concerning the nature of soil fertility was formulated by Mitscherlich in 1909 (10) and later by Spillman (11). These investigators arrived independently at the conclusion that plant growth follows a diminishing increment type of curve now known as the "yield curve." A law of diminishing increment type of curve, if not Mitscherlich's equation for it, is now generally used, at least in the upper two thirds to three fourths, the part of practical importance. There is some evidence that at times the curve may be sigmoid and that the first unit or so may actually give smaller yield increases than succeeding units when one starts with a soil almost completely deficient in the nutrient.

The most highly controversial part of Mitscherlich's work, however, is not the validity of the equation he used. One form of his equation can be expressed as follows: $\log (A - y) = \log A - cb$ where A is the total yield of all portions of the crop when the nutrient is not deficient, y is the yield when b amounts of a given form of the nutrient are present, and c is the proportionality constant. With this equation, for example, if the amount, b, of the nutrient present in the soil and the values of c and y are known, then the value of A, that is, the yield obtainable when the nutrient is not deficient, could be calculated. Or if, by a soil test, one could measure b, and then laid out two plots, one where the nutrient was adequate and one where b amounts of the nutrient were present, the values of A and y could be obtained and c could be calculated. This follows from the solution of the equation.

The highly controversial part is Mitscherlich's assertion that the value of c is a constant for widely varying conditions. In fact, he maintained that, for a given nutrient form, the value of c is a constant. Variations in all the other factors in crop growth, such as kind of plant, soil, season, and size of yield, were not supposed to influence the value. The assertion of the constancy of c represents a third major concept of the nature of soil fertility, especially since it resulted in the Mitscherlich-Baule percentage sufficiency concept. Given a constant value for c, it follows that one deficient amount of a nutrient always produces the same proportion (the same percentage) of that yield otherwise obtainable when the nutrient is adequate. Thus a given amount of a nutrient is "good for" a certain percentage of the obtainable yield as that yield varies in size with all other growth factors. Baule also concluded that when more than one nutrient was deficient, the final percentage sufficiency is the product of the individual sufficiencies (1). For example, suppose potassium is adequate for 90 per cent of a yield and phosphorus for 80 per cent. Then the final yield is 80 per cent of a 90 per cent yield, or 72 per cent of the yield obtainable when both nutrients are adequate.

Obviously, if this percentage sufficiency concept is correct, Liebig's concept of the limiting nutrient is wrong and vice versa.

For all except the area of extreme deficiencies, a diminishing yield increment type of curve appears plausible in light of what is now known about soil fertility and plant growth and composition. But when a nutrient that is very deficient is added to an otherwise fertile soil, the plant may respond by an increase in growth, or in percentage composition, or in both. If the initial increments at first increase percentage composition at a relatively faster rate than they do the yield, and there follows a period where the yield is increasing at a relatively faster rate than the composition, and the final increments of the nutrient again increase the composition at a relatively faster rate than the yield, a sigmoid type of growth curve would be produced.

To the greatest majority of those interested in soil fertility the idea that a given amount of a nutrient could be sufficient for a certain percentage of a yield, regardless of the size of that yield, has appeared fantastic. Except for a scant few who have exploited the work of Mitscherlich and Baule, their percentage sufficiency concept has received little credence in the soil fertility literature. No one has explained how such a relationship could possibly hold, if it does hold, or has appraised the conditions which must be constant in order for it to hold. The limiting nutrient concept has always appeared the more plausible.

This paper develops a concept which attempts to resolve the differences between Liebig's limiting nutrient concept and the Mitscherlich-Baule percentage sufficiency concept and to make possible a rational interpretation of those data which appear to "prove" either one or the other correct. This concept concerning the nature of soil fertility is best developed and explained by first considering the nature of a plant as it grows and "forages" for the available forms of the nutrients in the soil, and the part that the properties of these available forms play in this foraging.

SIGNIFICANCE OF NUTRIENT MOBILITY

The mobility of nutrients in soils is one of the most important single factors in soil fertility relationships. The term "mobility," as used here, means the over-all process whereby nutrient ions reach sorbing root surfaces, thereby making possible their sorption into the plant. Thus the term involves the solution or exchange of the nutrient as well as its movement to the root surfaces. A correlative process, just as important, is the growth of the roots and extension of the sorbing root surfaces into areas where the nutrients occur. These two processes, complementing each other, largely determine the soil fertility requirements of a plant.

For purposes of discussion, the term "yield possibility" is defined as the yield obtainable when all nutrients are adequate, yet not in harmful excess. This eliminates nutrient sufficiencies or deficiencies as determinants of the yield possibility. As defined, the yield possibility is not a hypothetical maximum yield. It is a value which can vary with all factors in yield except nutrient supply. Used in this sense it becomes the value of A in Mitscherlich's yield equation, $\log (A - y) = \log A - cb$, when no nutrients are deficient. From the viewpoint of Liebig's "law of the limiting nutrient," it is the yield obtainable when no nutrients are "limiting." In any following discussion involving the requirements of any one nutrient, it is assumed that all other nutrients are adequate unless otherwise stated.

In terms of the Liebig concept a different soil level of a nutrient is needed for each different yield possibility, and c varies in the equation. According to Mitscherlich's concept, one specific soil level of a certain nutrient form can be adequate for any yield possibility, and c remains constant as yield possibilities vary. For purposes of discussion, this soil level of a nutrient needed to produce the yield possibility will be defined as the "soil nutrient requirement" although it is recognized that practically it should be considered as the amount needed for about 98 per cent of the yield possibility because of the nature of the yield equation.

It follows from these definitions and the equation that any factor which varies the soil nutrient requirement will vary the value of c and that such factors must be held constant if c is to remain constant as yield possibilities vary.

Mitscherlich's assertions for constancy of c are subject to test by field experiments, and such tests have been made. But if even one factor, other than nutrient form varies the soil nutrient requirement, and if that one factor is allowed to vary in a series of experiments, then a constant c value will not be obtained and Mitscherlich's concept cannot be verified. Regarding such field experiments it is sufficient to say that so far Mitscherlich's percentage sufficiency concept has been neither fully verified nor fully disproved. It is highly probable that this situation has resulted from the fact that one or more unrecognized factors in yield must also be kept constant if the soil nutrient requirement is to remain constant. This paper analyzes certain soil and plant properties with respect to their probable influence on the soil nutrient requirement, hence on the possibility of c's remaining constant.

The varying mobility of the nutrients in soils and the varying ability of plants to acquire nutrients through variations in the extensiveness and intensiveness of their root systems involve factors that should vary the value of the soil nutrient requirement and hence the value of c.

Nature of available soil forms of nutrients and their relative mobility

The available soil forms of the nutrients have been defined as those forms whose variations in amount are responsible for significant variations in yield and response (2). The availability of these soil forms, however, involves not only their chemical and physical nature but also the ability of the plant to "forage" for them with its root system.

Of all the available soil forms, nitrate nitrogen has, most generally, the highest availability. Nitrate nitrogen is highly soluble and not markedly adsorbed by the soil clay or soil organic matter; hence it is freer to move with and diffuse through the soil water. Rains move it downward and, as the soil dries, it starts to move back toward the surface. All these processes help to give nitrate sufficient mobility so that plants can reduce the soil nitrate level within their root-feeding zones to a very few parts per million. Drought can temporarily immobilize nitrate nitrogen. Excluding nitrates that may be lost by leaching or used in soil biological processes, the "net amount" of nitrate which a soil must supply need not be more than a few pounds per acre larger than the crop will remove. In most soils, nitrate nitrogen can be considered the ultimate available form of nitrogen. In this sense, the chemistry of nitrate nitrogen can be considered the chemistry of available nitrogen.

In soils of a humid region that have sufficient clay and organic matter to adsorb nutrient ions like potassium, calcium, magnesium, and phosphate, or have conditions for their precipitation, only the unadsorbed ions like the nitrate and sulfate have a relatively high mobility in the soil. The adsorbed and relatively insoluble forms of the nutrients are much less mobile in the soil, ion movement being slight over a short period. Cations move as companion ions of unadsorbed anions such as the nitrate, chloride, or bicarbonate. Cations like potassium, magnesium, and calcium are held on the surfaces of the negatively charged colloidal clay and organic matter in the soil as exchangeable cations. They can be replaced by, and are in equilibrium with, the cations in the soil water. The amount of each cation in the soil water at equilibrium is controlled by the kinds and amounts of the electrolytes in the soil water, the amounts of the different exchangeable cations present, and their relative ease of release (3).

The electrolyte concentration of a typical soil in humid regions is usually low, varying mostly with the amounts of nitrate, bicarbonate, and sulfate anions present, except as an anion like chloride is added in fertilizers. Even though the electrolyte concentration is low, however, the equilibrium between the electrolyte cations and the exchangeable cations provides a means whereby nutrient cations can be renewed as their sorption by the root surface disturbs the equilibrium. This renewal of the nutrients at the root surface is, for the exchangeable cations and anions, a very important process, even though effective from only a limited distance during the active life of the root. A single root hair, to be functional, must secure many times the amounts of the nutrients that are to be found on the immediate surface of a clay mineral particle with which it may be in contact. Regardless of whether the root and clay surfaces are so close that contact exchange, as postulated by Jenny and Overstreet (7), can take place, the amount obtained from the immediate contact would be small and insufficient to make the root functional. The significant source of nutrients to the root surface comes from movement or diffusion into the film of water between the root surface and the soil surface.

The exchange reaction itself is very rapid once contact between adsorbed and free ions takes place. It is the necessity for water movement and diffusion (possibly including "exchange diffusion") to renew the exchangeable nutrients in these root surface sorption zones that limits the effectiveness of the exchangeable ions and makes the level required for maximum yields many times higher than the amount needed in the crop. It is also supposed that phosphates are adsorbed on the clay minerals as exchangeable anions or on the surfaces of iron and aluminum oxides or hydroxides and represent a similar case.

A third case, in addition to the soluble and adsorbed forms, is that of a root hair surface feeding, for example, on an adjacent particle of rock phosphate, tricalcium phosphate, or dicalcium phosphate. As phosphate molecules are dissolved from the surface of the particle and the phosphate anions are taken up by the root surface, the next layer of phosphate molecules can dissolve, and feeding would be limited mainly by the rate of solution rather than by ion movement. This, in effect, limits phosphate mobility.

In terms of "availability," a form like exchangeable potassium is highly available in the area of immediate contact. Its availability decreases with distance from the root surfaces, and as nearby exchange surfaces are depleted, they compete with the root surface for any new potassium entering the area. Its availability is a matter not only of chemical form, but also of the area of sorbing root surface for the whole plant. Under the conditions of the Neubauer method, virtually 100 per cent of the exchangeable potassium can be removed, because of the high root concentration relative to the amount of soil used. Under field conditions, approximately 5 to 20 per cent of the exchangeable potassium is taken up. Thus, to say a certain form of a nutrient is available implies no certain degree of availability that is independent of soil-plant relationships. Because different forms of the nutrients differ in their "exchangeability," or solubility, and hence in their mobility, they will also differ in their soil nutrient requirements. If the soil nutrient requirement varies, then the value of c will vary. Mitscherlich recognized nutrient form as the only factor varying the value of c.

Root sorption zones and nutrient mobility

In a report on a study of exchangeable potassium it was pointed out that the available soil forms of the nutrients could be divided into two groups.[1] One group consisted of nutrients relatively mobile in the soil, like nitrate nitrogen; the other, of nutrients relatively immobile, like exchangeable potassium and the adsorbed forms of phosphate. It was postulated that these extremes in mobility created two root sorption zones. One zone included the whole volume of soil within the major part of the root system. From this zone, called the ***root system sorption zone***, the root system effectively obtains relatively mobile nutrients. The other zone, or rather zones, were the thin volumes of soil adjacent to each root, or root hair surface, from which the roots effectively obtain the relatively immobile nutrients. They were called the ***root surface sorption zones***. These two kinds of zones are schematically illustrated in figure 1.

It was considered that plant roots could almost quantitatively remove the relatively mobile nutrients from within the root system sorption zone. This would mean that, excluding leaching or other losses from the soil, such as biological fixation, the "net" soil nutrient requirement as already defined would be close to the amount contained in the crop.

For the relatively immobile nutrients it was considered that effective removal decreases rapidly with distance from the root surface, thus limiting the total amount removed to a small part of the amount of the relatively immobile nutrients present.

Kind of plant and nutrient mobility

Different species and varieties of plants vary in their rooting habits. Generally speaking, however, they are bushy and dense directly beneath the plant and, extending away from the dense part of the root system, they are less numerous and slender. If plants vary in their rooting habits, they should also vary in their ability to obtain the relatively immobile nutrients, hence, in their soil nutrient requirements for these nutrients.

But when plants of any kind are grown so close together that a relatively mobile nutrient can be almost completely removed, then the yield and percentage composition of a crop will largely determine the crop's "net" requirement for that nutrient.

[1] Bray, R. H. The chemical nature of soil potassium in relation to its availability in Illinois soils. 1940. [Unpublished Ph.D. thesis. Copy on file University of Illinois, Urbana.]

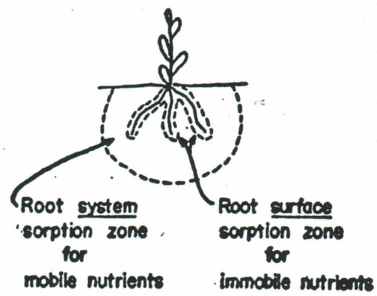


Fig. 1

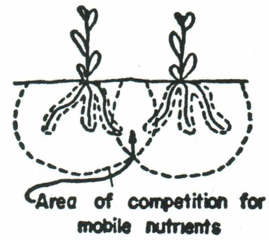


Fig. 2

Fig. 1. Root Sorption Zones
Fig. 2. Root System Sorption Zones Overlapping

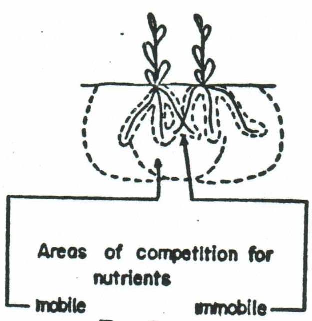


Fig. 3

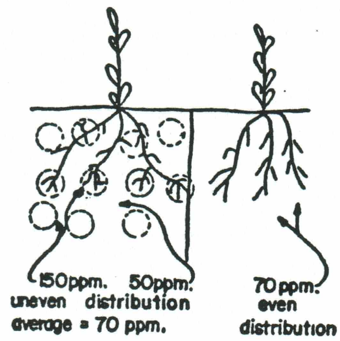


Fig. 4

Fig. 3. Root Surface and Root System Sorption Zones Overlapping
Fig. 4. Fertility Patterns Having Same Soil Level of an Immobile Nutrient

Plant competition sequence and nutrient mobility

It was also postulated that competition between adjoining plants occurs in three stages, which were called the "plant competition sequence." When plants are far enough apart so that neither of their root sorption zones overlap (interpenetrate), no competition for nutrients (or water) occurs. When the root *system* sorption zones of adjacent plants interpenetrate, competition for the relatively mobile nutrients occurs. Competition for the relatively immobile nutrients occurs only as the root *surface* sorption zones interpenetrate. (See figs. 1–4.) Depending on the planting pattern and rate of planting, plants can grow (*a*) without competing with each other for any nutrients, (*b*) effectively competing for the relatively mobile nutrients only, and (*c*) competing for both the relatively mobile and relatively immobile nutrients.

When a plant is grown under conditions where it does not compete with other plants for nutrients, its soil nutrient requirements will be at a minimum. As plants are planted closer and closer together, and yields increase, competition for the relatively mobile nutrients is initiated and intensified. An amount adequate for the lower rate of planting rapidly becomes a deficient amount, placing an absolute limitation on yield. But the relatively immobile nutrients, such as exchangeable potassium, change much more slowly in their sufficiencies, hence in their soil nutrient requirements.

Although the effect of competition between plants is much greater for the relatively mobile nutrients, competition affects the soil nutrient requirements of all nutrients and is a determinant of their soil nutrient requirements, hence of the value of *c*.

Stage of growth and nutrient mobility

If the root system is least efficient in nutrient sorptions relative to its needs at a certain stage of growth, this may not necessarily affect the soil nutrient requirements for a relatively mobile nutrient. But the concentration of a relatively immobile nutrient, assuming even distribution throughout the soil, would have to be higher for this stage of growth than for any other. Hence, the stage of growth at which the plant needs the highest nutrient concentration would determine the soil level of a relatively immobile nutrient needed for maximum yields. Usually an immobile nutrient deficiency affects the earliest stage of growth the most (6).

Nutrient mobility and the fertility pattern

With certain exceptions, an even distribution of a limited amount of a relatively immobile nutrient throughout the soil does not provide the highest availability for root sorption. Concentration increases the "exchangeability" or "solubility" of an adsorbed form of a nutrient (8). If such a nutrient is concentrated into patches distributed favorably for root sorption, the chemical availability of that nutrient has been increased in comparison with the same amount mixed thoroughly in the soil. Such variations in the nutrient concentration (fertility pattern) can, therefore, change the amount needed and, hence, change the soil nutrient requirement.

Soil and seasonal conditions and nutrient mobility

Differences in the favorableness of the season or in the physical favorableness of the soil can greatly vary the yield possibility. Where other yield factors are held constant, variations in the yield possibility caused by the soil and seasonal factors will result from variations in the size of plant.

Variations in yield, resulting from these factors, will obviously create a variation in the amount of a relatively mobile nutrient needed, because size of yield is directly associated with mobile nutrient requirements. But if a larger plant is accompanied by a larger, more effective root system, which obtains extra nutrients by exploring new soil areas, then it is conceivable that this yield increase may not materially increase the soil nutrient requirement for the relatively immobile nutrient.

Liebig's "law of the limiting nutrient" and nutrient mobility

When plants are planted sufficiently close together so that their root system sorption zones blend to form a single zone, as is usually the case, almost complete uptake of a relatively mobile nutrient can take place. When virtually all of a mobile nutrient has been sorbed, further growth can take place only through a dilution of the concentration of that nutrient within the plant, and the product of the yield times the percentage composition (the crop content) remains constant. Given two mobile nutrients, both potentially deficient for the achievement of the yield possibility, the one that first starts to limit the yield becomes "the limiting nutrient" according to Liebig. As the minimum possible composition is reached, no further increase in yield is possible. If at this point the other potentially deficient nutrient is still adequate for the yield obtained, it will not become actively deficient; its potential deficiency will not be realized. But if the second nutrient becomes deficient before minimum composition, with respect to the first nutrient, has been reached, both could help limit yields. Whether a soluble nutrient needed in trace amounts will also act as a relatively mobile nutrient is a problem needing further study.

Thus the relatively mobile nutrients tend to follow Liebig's "law of the limiting nutrient" and their "net" soil nutrient requirements are determined almost entirely by the magnitude of the yield possibility and its percentage composition, that is, the crop content. This value, in turn, is determined by the factors that determine the yield possibility, namely, those associated with the kind of plant, the planting pattern and the rate of planting, the physical favorableness of the soil, the favorableness of the season, and the management.

Nutrient mobility and Mitscherlich-Baule percentage sufficiency concept

If a nutrient is sufficiently immobile, the root surface sorption zones will be small and their sum may represent only a fraction of the total soil in the root system sorption zone. In this case they will contain only a fraction of the total amount of a relatively immobile nutrient present in the soil, assuming, for purposes of discussion, an even distribution of the nutrient. This means that any increase in the intensity of the root system within the root system sorption zone will result in new roots and root hairs penetrating into fresh soil areas that still contain the original immobile nutrient concentration.

Now, if the concentration of this relatively immobile nutrient is such that, as a plant starts to grow, its roots obtain just enough of the nutrient, and if, as it continues to grow, the new roots of the larger root system tap sufficient new soil areas to continue to obtain just enough of the nutrient, then this concentration would represent the soil nutrient requirement.

Furthermore, it means that any variations in the yield of that plant (in its size at maturity) would not change the soil nutrient requirement. It would remain a constant as yields varied.

This is an idealized case which illustrates the significance of relative immobility. It infers the possibility of c's remaining a constant in Mitscherlich's yield equation, as was maintained by Mitscherlich and Baule. If this were so, then the soil nutrient requirement would be the value of b when y equals the yield possibility in the equation $\log (A - y) = \log A - cb$, and any smaller value of b would always produce a proportionally lower yield, that is, would be sufficient for a certain percentage of yield *A*. The broad assertion of constancy for *c*, as yields vary because of any variable except nutrient form, is the controversial aspect of the percentage sufficiency concept.

In the preceding discussions concerning nutrient mobility and plant root sorption, many points have been raised which challenge the validity of this broad assertion.

If the writer's analysis of the significance of the factors in yield is essentially correct, the following points disagree with the assertion that *c* can be universally constant for a given form of a nutrient:

1. Not all nutrient forms can follow a percentage sufficiency concept; the relatively mobile forms should follow the "law of the limiting nutrient."
2. Even a restricted demonstration of the constancy of *c* for a relatively immobile nutrient should be impossible if a relatively mobile nutrient is actually (not potentially) deficient.
3. Since plants vary in the nature of their root systems, the value of *c* should vary with the kind of plant.
4. Variations in the rate of planting and the planting pattern should vary competition for the nutrient and hence vary the value of *c*.
5. Mitscherlich recognized that variations in the form of the nutrients varied the value of *c*. But variations in their distribution within the soil, that is, in the fertility pattern, should also vary the value of *c* for the relatively immobile nutrients.

On the other hand, it was considered that those variations in the yield of a crop which are caused by differences in the size of each plant, when they are caused by variations in the favorableness of the soil and season, may not cause significant differences in the soil nutrient requirements, hence in *c*.

When these points are analyzed, it is found that the variables believed likely to vary the value of *c*, hence the value of the soil nutrient requirement, are those associated with the kind of plant, the planting pattern and rate, and the form of the nutrient and its relative distribution in the soil in relation to the planting pattern. Also, the nutrient form must be relatively immobile.

These are the groups of factors believed to be determinants of the soil nutrient requirements for relatively immobile nutrients, hence the factors that must be held constant if *c* is to remain constant as yields vary. This puts definite limits to the yield range within which *c* can remain a constant. Only the yield variations caused by the favorableness of the soil and season remain to be considered. These variations result from differences in the *size of each plant* at the time the yield is taken. An unfavorable season or a soil of poor physical condition can restrict yields. The opposite conditions can increase yields. As the size of each plant increases and new roots penetrate new soil areas, it becomes possible for that concentration of the nutrient, evenly distributed, which is just adequate for the smaller plants, to be equally adequate for the larger plants and vice versa. This means that the soil nutrient requirement remains constant as yields vary in size due to variations in factors concerned with the physical nature of the soil and the season. If this is so, then the soil nutrient requirement for a relatively immobile nutrient remains constant and the value of *c* remains constant in the yield equation.

Assumption of proportionate feeding

A single assumption can explain how it is possible for the soil nutrient requirement to remain constant. If it is assumed that, under certain conditions, variations in yield are accompanied by corresponding variations in the ability of a plant to obtain the relatively immobile nutrients, then their soil nutrient requirements will remain constant, and the value of c in the Mitscherlich yield equation will be a constant.

The conditions that must be held constant for this assumption to hold are as follows: The plant must be of the same kind and it must be planted at a given rate in a given pattern. The form (mobility) of the nutrient must be the same and its distribution within the soil in relation to the planting pattern must be the same. Variations in the physical nature of the soil and in the season should not be too extreme.

NUTRIENT MOBILITY CONCEPT OF SOIL-PLANT RELATIONSHIPS

The significance of nutrient mobility, with respect to its influence on the soil level of a nutrient needed for the achievement of the yield possibility, has been discussed from the viewpoint of factors in yield as well as the Liebig and Mitscherlich concepts. It has been shown that nutrient mobility imposes limits to the applicability of the Liebig and Mitscherlich concepts. Explanations for these limits have been given. Neither concept by itself is comprehensive enough to explain the relationships determining the soil nutrient requirements for plant growth. A new concept embracing these two concepts, as well as giving the significance of the nature of the soil forms of the nutrients in relation to nutrient sorption by plants, has therefore, been formulated.

This concept can be stated 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.

Though this concept of soil-plant relationships appears to be mainly concerned with nutrient mobility, it is equally concerned with a plant's ability to "forage" for nutrients as it grows. The nutrient mobility concept, therefore, is comprehensive, embracing all the growth factors, although with a more immediate concern for the amounts of the available forms of the nutrients needed for maximum growth at optimum composition. The concept furnishes a framework within which studies of soil fertility and soil productivity can be made with the possibility of their being intepreted in terms of those factors which are determinants of the soil nutrient requirements (hence fertilizer needs) and of the yield possibility.

The significance of the nutrient mobility concept is as follows. At one end of the mobility scale are the relatively mobile nutrients, of which nitrate nitrogen is a good example when water is adequate. Potassium might be just as good an example when the soil has little or no base-exchange (cation-adsorption) properties or has a high electrolyte content. With normal planting patterns for the usual farm crops, it is considered that a relatively mobile nutrient is rather thoroughly explored for and taken up regardless of normal variations in the size of the plants' root sorption systems caused by other factors. This implies a high availability. The "net" soil nutrient requirement (not including leaching losses or utilization by soil reactions or microorganisms) will not be much greater, therefore, than the crop content. One "net" amount is sufficient for a crop of only one size and percentage composition.

At the other end of the mobility scale are forms that can act like relatively immobile nutrients. Examples are exchangeable potassium, calcium, magnesium, the absorbed and "acid-soluble" soil forms of phosphorus, and (temporarily) ammonia. When these forms of the nutrients possess a low mobility, as they will in humid soils of low electrolyte content, their soil nutrient requirements are reasonably constant and many times larger than the crop content, as yields vary within the limits imposed by the nutrient mobility concept. Also, as yields vary, a deficient amount of a relatively immobile nutrient will maintain its relative deficiency, that is, one deficient amount will tend to be sufficient for a certain percentage of that yield which is possible when the nutrient is not deficient.

The middle part of the mobility scale is concerned with situations where the capacity of the soil to adsorb nutrients is too small to permit them to act like relatively immobile nutrients yet too large for them to act exactly like relatively mobile nutrients. In such situations, neither the limiting nutrient concept nor the percentage sufficiency concept can be used to interpret quantitatively soil fertility relationships.

One limitation to the concept must be recognized. Planting rates cannot be increased indefinitely and still permit the percentage sufficiency concept to operate. This follows from the fact that as the proportion of the relatively immobile nutrients obtained by the crop becomes large in relation to the amount present, the percentage sufficiency concept can no longer apply. For example, in the Neubauer method for measuring available nutrients, the planting rate is so high, in proportion to the amount of soil used, that approximately 100 per cent of the exchangeable potassium is removed.

Besides the mobility of the nutrient, the nature of the plants' root systems must be considered. An extreme example is a crop growing in only 6 inches of soil underlain by solid rock or an impenetrable claypan. In effect, this causes the roots of the same and adjacent plants to compete more intensively and thus decrease the value of c, as compared to deeper, more nearly "normal" types of root development. Such possibilities are the reason for the qualification ". . . and relatively similar soil and seasonal conditions prevail" in the statement of the nutrient mobility concept.

That there is a strong tendency for a relatively immobile nutrient to act percentagewise is undoubted. But the assertion that c can be a constant for all conditions, except differences in form, as made by Mitscherlich, is not tenable in view of the limitations discussed.

It is surprising, therefore, in view of these limitations, to find a close association between the amounts of exchangeable potassium and the percentage yield of corn following clover in Illinois soils where variations are wide in clay content, organic matter, cation-exchange capacity, degree of saturation with the different cations, rainfall distribution, and other factors (4). Apparently, "relatively similar soil and seasonal conditions" can include a rather wide range of these conditions if it is desirable to have a value of *c* that will hold for "average" conditions. The average value of *c* for all trials in 1933–1941 was 0.0055. A later unpublished study of the 1943–1947 period gave an average value of 0.0053. For both periods the standard error was the same, ±5 per cent. When the fields included in the later studies were separated into three groups according to the maturity of their soils, each group average showed no significant difference in *c* value and the standard deviation increased from 0.0011 to 0.0018 as the maturity increased. Another study indicated similar relationships for another nutrient, phosphorus, and for other crops (5). The *c* values obtained varied with the kind of crop. These values must be confirmed, however, since the possibility exists that nitrogen, a "limiting" nutrient, was deficient for the other crops.

When the situations under which these relationships were obtained are analyzed in light of the factors previously discussed, it is found that the main variables causing yield differences in corn were those thought not to change the soil nutrient requirements for the relatively immobile nutrients. These were the favorableness of the soil and the season. Those factors believed to vary the soil nutrient requirement, such as planting pattern, form of nutrient, and fertility pattern, were being held reasonably constant.

SUMMARY

Extremes in mobility of the available forms of soil nutrients give rise to two kinds of root sorption zones for plants. One is the large volume of soil occupied by the major part of the plants' root system and is called the "root system sorption zone." The other is a relatively thin layer of soil adjacent to each root surface and is called the "root surface sorption zone."

From the root system sorption zone the roots of a plant can remove almost quantitatively the highly mobile nutrients. This results in their "net" requirement being almost equal to the crop content at maturity, that is, one amount is sufficient for only one yield of a given percentage composition. Variations in yield do not cause any marked variations in the plant's ability to secure a highly mobile nutrient. Such nutrients can act as "limiting nutrients" in the sense given in Liebig's "law of the limiting nutrient."

From the root surface sorption zones, the roots effectively obtain the relatively immobile nutrients. The sum of these small root surface sorption zones represents only a small part of the soil, hence the roots "feed on" only a small part of the relatively immobile nutrients present. The amounts that must be present for maximum yields are, therefore, many times larger than the crop content. Variations in plant size (yield) can vary the plant's ability to obtain the relatively immobile nutrients. One amount is not just adequate for one yield of a given percentage composition, it can be just adequate for a wide range of yields, provided the plant's ability to obtain it is proportional to the size of the plant. When this occurs, a relatively immobile nutrient can act percentagewise in soil-plant relationships, that is, it can follow the Mitscherlich-Baule percentage sufficiency concept.

These relationships have been integrated into a concept of nutrient mobility which defines the limits within which the Liebig and the Mitscherlich-Baule concepts can be expected to hold and explains why the concepts hold and why the limits have been imposed.

REFERENCES

(1) Baule, B. 1918 Zu Mitscherlichs Gesetz der physiologischen Beziehungen. *Landwirtsch. Jahrb.* 51: 363–385.

(2) Bray, R. H. 1938 New concepts on the chemistry of soil fertility. *Soil Sci. Soc. Amer. Proc.* (1937) 2: 175–179.

(3) Bray, R. H. 1942 Ionic competition in base-exchange reactions. *J. Am. Chem. Soc.* 64: 954–963.

√ (4) Bray, R. H. 1944 Soil-plant relations: I. *Soil Sci.* 58: 305–324.

(5) Bray, R. H. 1944 Soil-plant relations: II. *Soil Sci.* 60: 463–473.

(6) DeTurk, E. E. 1942 The problem of phosphate fertilizers. *Illinois Agr. Expt. Sta. Bull.* 484: 561–562.

(7) Jenny, H., and Overstreet, R. 1939 Cation interchange between plant roots and soil colloids. *Soil Sci.* 47: 257–272.

(8) Kurtz, L. T., DeTurk, E. E., and Bray, R. H. 1946 Phosphate adsorption by Illinois soils. *Soil Sci.* 61:111–124.

(9) Liebig, Justus von 1855 Die Grundsatze der Agriculturchemie. Braunschweeg.

(10) Mitscherlich, E. A. 1909 Das Gesetz des minimums und das Getsetz des abnehmenden Bodenertrages. *Landwirtsch. Jahrb.* 38: 537–552.

(11) Spillman, W. J., and Lang, E. 1924 The law of diminishing returns. World Book Co., New York.