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AGRONOMIC EVALUATION OF FERTILIZERS

PRINCIPLES & PRACTICES

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PRINCIPLES & PRACTICES

AGRONOMIC EVALUATION OF FERTILIZERS

G. L. Terman and O. P. Engelstad[1]

INTRODUCTION

The present emphasis on world food production requires high efficiency of all agronomic inputs. Because of the great importance of fertilizers as one of these inputs, it is essential that sound principles be used in fertilizer evaluation.

TVA chemists and chemical engineers have carried out research and development on new fertilizers and fertilizer production technology for 35 years. Much of the resulting information has been published in technical journals, fertilizer trade magazines, and books. During this same period, TVA and other agronomists and soil chemists have carried out numerous studies on the principles and methods for evaluating the nutrients in these fertilizers. Much of this continuing research has also been published. These results, together with those of other investigators, are summarized here.

The chief objective of this manual is to describe the principles underlying sound evaluation of fertilizers, especially in field experiments. In general, the same principles apply to fertilizer evaluation and soil fertility research under field, greenhouse, growth chamber, or laboratory conditions. Techniques and principles for evaluating fertilizers in greenhouse pot experiments have been described in another manual published by TVA (1966). Principles for various types of biological evaluation of nutrients in fertilizers have also been summarized (1962). Designs and techniques for carrying out various types of fertilizer and other experiments are covered more adequately in several textbooks on experimental design (see References).

[1]Agronomists, Soils and Fertilizer Research Branch, Div. of Agricultural Development

FERTILIZER CHARACTERISTICS IMPORTANT IN EVALUATION

Chemical compounds present in the more common commercial fertilizers are listed in table 1. The various compounds undergo many types of chemical reactions with soils and soil solutions.

The nature of products formed from these reactions and their availability to plants depend on both the kind of fertilizer and

Table 1. Compounds Present in N, P, K, NP, NK, or PK Commercial and Experimental Fertilizers.

Fertilizer Material	Representative Grades % N-P_2O_5-K_2O[a]	Water Solubility of N, P, or K (%)	Major Compounds Present
N Sources		N	
Anhydrous ammonia	82-0-0	100	NH_3
Ammonium chloride	26-0-0	100	NH_4Cl
Ammonium nitrate	33.5-0-0	100	NH_4NO_3
Ammonium sulfate	20.5-0-0	100	$(NH_4)_2SO_4$
Ammonium nitrate-lime	20.5-0-0	100	NH_4NO_3, $CaCO_3$, $Ca(NO_3)_2$
Calcium cyanamide	22-0-0	100	$CaCN_2$
Calcium nitrate	15.5-0-0	100	$Ca(NO_3)_2$
Sodium nitrate	16-0-0	100	$NaNO_3$
Urea	45-0-0	100	$CO(NH_2)_2$
S-coated urea	35-0-0	Variable	$CO(NH_2)_2$, elemental S
P Sources		P	
Phosphoric acid:			
Wet-process	0-55-0	100	H_3PO_4
Furnace grade	0-55-0	100	H_3PO_4
Super acid	0-79-0	100	H_3PO_4, polyphosphoric acids
Superphosphate:			
Ordinary (H_2SO_4)	0-20-0	85	$Ca(H_2PO_4)_2 \cdot H_2O$, $CaSO_4 \cdot 2H_2O$
Triple (WP H_3PO_4)[b]	0-45-0	87	$Ca(H_2PO_4)_2 \cdot H_2O$
Conc. (Furn. H_3PO_4)[b]	0-48-0	90	$Ca(H_2PO_4)_2 \cdot H_2O$
High-anal. (Super acid)	0-54-0	90	$Ca(H_2PO_4)_2$
Dicalcium phosphate:			
HCl process	0-40-0	4	$CaHPO_4 \cdot 2H_2O$, $CaHPO_4$
Electric furnace H_3PO_4	0-48-0	3	$CaHPO_4$, $CaHPO_4 \cdot 2H_2O$
Calcium metaphosphate	0-62-0	5	Vitreous Ca polyphosphate, $Ca_2P_2O_7$
Fused tricalcium phosphate	0-28-0	<2	Alpha and Beta $Ca_3(PO_4)_2$
Rhenania phosphate	0-33-0	<2	Ca silico-phosphates

Table 1. (continued)

Fertilizer Material	Representative Grades % N-P_2O_5-K_2O[a]	Water Solubility of N, P, or K (%)	Major Compounds Present
Serpentine phosphate glass	0-22-0	<2	Ca, Mg silico-phosphates
Basic slag	0-9-0	<2	Ca silico-carnotite
Colloidal "clay" phosphate	0-22-0	<1	Apatite, Al phosphates
Florida phosphate ore	0-32-0	<1	Carbonato apatite
K, NK, and PK Sources		K	
Muriate of potash	0-0-60	100	KCl
Sulfate of potash	0-0-48	100	K_2SO_4
K, Mg sulfate (Sulpomag)	0-0-23	100	$K_2SO_4 \cdot 2MgSO_4$
Nitrate of potash	13-0-44	100	KNO_3
Potassium polyphosphate	0-59-39	5	K polyphosphates
NP Sources		P	
Ammoniated ordinary superphosphate	4-14-0	35	$NH_4H_2PO_4$, $CaHPO_4$, reprecipitated apatite, $CaSO_4 \cdot 2H_2O$[c]
Ammoniated concentrated superphosphate	5-47-0 9-48-0	50) 50)	$NH_4H_2PO_4$, $CaHPO_4$, $(NH_4)_2HPO_4$, reprecipitated apatite[c]
Ammonium phosphate nitrate	30-10-0	100	$NH_4H_2PO_4$, NH_4NO_3, $(NH_4)_2HPO_4$
	25-25-0	100	$(NH_4)_2HPO_4$, NH_4NO_3, $NH_4H_2PO_4$
	28-14-0	100	
Ammonium phosphate sulfate	11-48-0	>90	
	13-39-0	>90	$NH_4H_2PO_4$, $(NH_4)_2SO_4$
	16-20-0	>90	
	16-48-0	90	$NH_4H_2PO_4$, $(NH_4)_2HPO_4$, $(NH_4)_2SO_4$
Diammonium phosphate	21-53-0	100	$(NH_4)_2HPO_4$
	18-46-0	>95	$(NH_4)_2HPO_4$
Ammonium polyphosphate	15-60-0	100	$NH_4H_2PO_4$, $(NH_4)_3HP_2O_7$, longer chain polyphosphates
Urea ammonium phosphate	34-17-0 29-29-0 25-35-0	100) 100) 100)	$CO(NH_2)_2$, $(NH_4)_2HPO_4$
Urea ammonium polyphosphate	36-18-0 30-30-0 22-44-0	100) 100) 100)	$CO(NH_2)_2$, $(NH_4)_3HP_2O_7$, $NH_4H_2PO_4$
Nitric phosphate	20-20-0	40	$CaHPO_4$, $NH_4H_2PO_4$, $Ca(NO_3)_2$, reprecipitated apatite[d]

[a]Convert N-P_2O_5-K_2O to N-P K by multiplying by 1.0-0.44-0.83.
[b]Triple (TSP) and concentrated superphosphates (CSP) are used interchangeably.
[c]Ando, J. and J. R. Lehr. *J. Agr. Food Chem.* 15:741-50. 1967.
[d]Ando, J. and J. R. Lehr. *J. Agr. Food Chem.* 16:391-98. 1968.

soil properties. Fertilizer placement, time of application, level of soil productivity, and many other factors affect crop response to nutrients in fertilizers.

Nitrogen and Potassium

Most N fertilizers are completely water-soluble. Ammonium N (NH_4^+) is initially adsorbed by soil organic matter and clay particles possessing cation exchange capacity. Under soil conditions suitable for good plant growth, however, NH_4^+ is rapidly converted by nitrifying bacteria to the nitrate form (NO_3^-).

As nitrate is not adsorbed strongly by soil particles, it moves freely in soil water. Consequently, even when N is applied in the ammonium form in bands, it soon becomes free to move throughout the root zone because of nitrification.

High mobility is also important in relation to time of N application. For maximum utilization of N fertilizer, plants must be in a vigorous growth stage soon after it is applied. Otherwise, the nitrate may move below the root zone, especially in humid areas or areas under irrigation. This loss, together with competition from microorganisms and weeds, often reduces crop recovery of N fertilizer as the interval increases between time of application and crop use.

Granule size and band placement of water-soluble N sources have little effect on crop use of N. Most soluble N sources are essentially equal in effectiveness for crops if incorporated with well-drained soils and if applied separately from the seed or plants so as to avoid seedling toxicity problems.

Special problems concerned with volatilization losses of N from surface-applied fertilizers, application of anhydrous ammonia, and slow-release N sources will be discussed in a later section (Special Problems Affecting Nutrient Source Evaluation).

All of the common potash fertilizers, such as chloride (muriate, KCl) or sulfate (K_2SO_4) also are water-soluble. Like ammonium N, most of the K is adsorbed near the application point by cation exchange minerals and organic matter. It thus becomes "exchangeable" K.

However, unlike ammonium N, which nitrifies to the mobile nitrate form, K continues to be held by the soil and is relatively immobile. It, like other adsorbed nutrient ions, enters the root

after passing to the soil solution following an "exchange" with another ion, such as hydrogen (H^+). Leaching of applied K usually is not considered a problem, except in very sandy or gravelly soils.

The exchangeable fraction of soil K is readily available to crops. Another fraction of soil K is adsorbed strongly on soil particles and is slowly available to crops. Only the K fraction which becomes a component of the crystal lattice or which is trapped between layers of soil minerals may be considered fixed, or unavailable to crops.

Only in K-deficient, high K-fixing soils is crop recovery of applied K appreciably poorer from broadcast than from band applications. Likewise, only with such soils is there any agronomic advantage of granular over fine-textured forms.

The value of common K sources tends to be similar except for certain crops whose quality is adversely affected by too much chloride. With tobacco, potatoes, and sugar beets the sulfate source, nitrate (KNO_3), or metaphosphate (KPO_3) may be preferred.

Phosphorus

In contrast to N and K, P compounds in fertilizers vary widely in solubility. Phosphate rock is essentially insoluble in water. Various sources vary widely in dissolution in the ammonium citrate (AOAC method) solution used by chemists to determine available phosphate in fertilizers. At the other extreme of the water-solubility scale are ammonium phosphates, which are entirely water-soluble.

Granule Size-Water Solubility Effects—Research has shown that the effectiveness of phosphate fertilizers of varying solubility is closely related to size of fertilizer granules. In acid soils, percent recovery by plants of water-soluble phosphates usually increases with increase in granule size (increase in amount of P per granule) up to about 5 mm in diameter.

The advantage of water-soluble phosphates for early growth response seems to result from rather high concentrations of P near young seedlings. For example, P concentrations as high as 100,000 ppm in soil may be present in a band of soluble phosphate. In contrast, soils normally have less than 2 ppm in solution.

In the case of water-soluble phosphates, effect of granule size depends on differences in reaction products, and on the volume

of soil into which the fertilizer P moves. Phosphate granules react with only a small volume of adjacent soil particles. A normal field application of granular water-soluble fertilizer applied broadcast affects less than 2% of the total soil volume. Obviously, the amount of soil affected is much less when either fine or granular fertilizer is applied in bands. In fact, the least amount of soil is affected when granular, water-insoluble phosphates are banded.

Since dissolution of a granule depends upon transport of water to it, a large granule will take longer to dissolve than a small one. Consequently, soil immediately adjacent to a large granule will have a concentrated P solution for a longer period than soil next to a small granule. The final result of these conditions is that more fertilizer P will react with a unit quantity of soil adjacent to large granules than with the same quantity of soil adjacent to a larger number of small granules or solution. Hence, reaction products adjacent to large granules may be higher in P and of more value to plants than those adjacent to small granules.

Crop response to water-insoluble phosphates, such as dicalcium phosphate, generally increases as the granule size is reduced. The granule surface area per unit of applied P increases sharply as the granule size decreases. Figure 1 summarizes the relationships between granule size and water solubility of P fertilizers in acid to neutral soils.

Banding of water-insoluble phosphates commonly results in poorer crop response than does mixing into the soil. Fertilizer P broadcast and mixed into the soil comes in contact with a much larger volume of soil than when it is banded and therefore tends to dissolve (and become fixed) more rapidly. Growth response of young plants to water-insoluble phosphates is usually low because such sources do not provide high enough concentrations of soluble P for immediate crop uptake.

Most of the differences among phosphate fertilizers as sources of P for crop growth can be explained by granule size and solubility relationships. Content of iron and aluminum oxides, pH, and texture are important soil properties.

Placement—As evidenced by widespread use of band-applied starter fertilizers, many farmers want rapid, early crop growth. Whether this early growth response will affect final crop yield depends on additional factors of soil, climate, crop, and length of season. Rapid, early growth helps to reduce

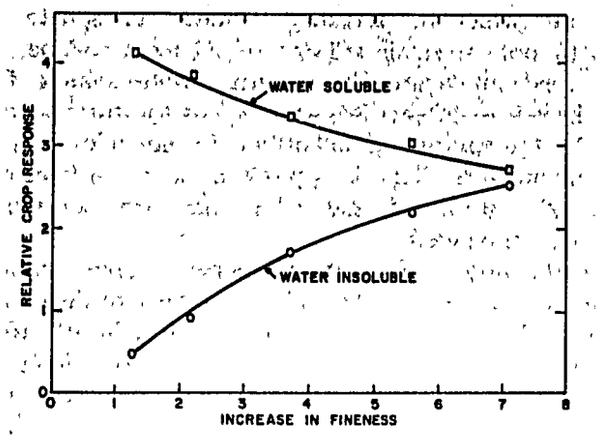


Figure 1. Relative Response in Greenhouse Pots to Water-Soluble and Water-Insoluble Phosphates. Granules From –9+14 to –50 Mesh Were Compared (fineness = reciprocal of radii of granules, mm.).

competition from weeds, diseases, and insects, and provides a larger leaf surface area as a photosynthetic base for subsequent growth. Where most of the fertilizer is bulk-spread and plowed under, good results also have been obtained with small amounts of soluble fertilizers placed with the seed. Water-soluble P is essential for this early growth response, especially in cold soils in early spring. Fertilizers having less than about 40% of the P in water-soluble form are not very satisfactory for this use. Similar agronomic response may be expected from similarly placed fluid and solid fertilizers of equal solubility.

Presence of N or K salts in granules containing water-insoluble phosphate tends to increase the surface area per unit of fertilizer P and thus increases P availability. Ammonium salts in soluble phosphate granules or bands also tend to increase P uptake by plants; this phenomenon has been attributed to stimulation of root growth, increased metabolic activity, and lower pH in the rhizosphere.

Secondary- and Micronutrients

Inconsistent results from field experiments comparing sources and carriers of secondary- and micronutrients are of

frequent occurrence. Lack of adequate and consistent response to the nutrient under test is usually the primary problem. This is often compounded by the problem of measuring rather small differences in yield at high yield levels, where micronutrient deficiencies are most likely to occur.

Multiple variables in the fertilizers under test and lack of experimental precision have no doubt been contributing factors. The results obtained would indicate that much of the information on source comparisons and principles affecting the use of nutrients by crops will continue to be obtained through laboratory and greenhouse research.

Oxidized forms of B and S and cations, such as Ca, Mg, and Mn, are similar in mobility to K and less mobile than nitrate-N. A third class, such as Cu, Fe, and Zn, have low mobility and resemble P in their availability relationships.

NEED FOR FIELD EVALUATION OF FERTILIZERS

In the United States, TVA, the U. S. Department of Agriculture, state universities, and fertilizer companies have carried out a tremendous amount of research on fertilizers. The same is true of various groups in a number of other countries. As a result, much information is available on the forms of nutrients in fertilizers and their agronomic value.

Results of solubility tests, petrographic observations, and greenhouse pot growth tests should be fully utilized before deciding whether the more costly and time-consuming field experiments are necessary for evaluating new fertilizers.

Many "new" fertilizers are recombinations of compounds that have already been studied extensively. As a result of this accumulated information on fertilizer and soil properties, the agronomic behavior or such "new" fertilizers can be predicted rather accurately in most cases. This can be inferred from data on compounds present, solubility, granule size characteristics, and response in pot experiments. Extensive field evaluation of such fertilizers is largely unnecessary, except as a means of demonstrating to fertilizer industry representatives, extension specialists, and farmers that the fertilizer is satisfactory if used properly under practical farm conditions. (Tropical soil areas may be an exception to this generalization.)

For example, urea ammonium phosphate (UAP) grades consist largely of various mixtures of urea and diammonium phosphate (DAP). Laboratory and greenhouse results indicate that UAP exhibits the properties of both urea and DAP, as might be expected. Results from field experiments have confirmed this. It thus appears that field evaluation on most soils of nutrients in products having well-known properties may be of value only in relation to method and timing of application for certain specific crops and cropping situations.

If fertilizers are different formulations of well-known compounds, a critical examination should be made of each "new" fertilizer to determine if any agronomic field evaluation is actually needed. However, when new compounds or new factors are introduced, specific problems will continue to occur which will require research under laboratory, greenhouse, and field conditions. Slow-release N fertilizers are an example of this need.

Demonstrations vs. Replicated Experiments

Perhaps the basic requirement for successful fertilizer or soil fertility demonstrations or experiments is to have a specific hypothesis or premise in mind in order to rule out haphazard treatment comparisons. A set of comparisons may be called a demonstration, an experiment, a test, or a trial, but the important point is whether the results will be meaningful in terms of the hypothesis or the problem to be solved. If treatment comparisons, experimental design, and growth conditions are not used from which valid results can be obtained, the initial hypothesis is not important, or even relevant.

For example, the hypothesis may be adopted that water solubility of P fertilizer is essential for a certain soil-crop-climate situation. Experimental fertilizers covering a wide range of solubility would then be selected to test the hypothesis. Soils would be selected on which adequate yield response to applied P can be expected, and other variables would be eliminated insofar as possible.

Basic principles of the experimental method include: (a) the need for replication of each treatment to provide a valid estimate of experimental error from which the significance of treatment differences can be determined; and (b) location of treatments at random within an experimental area to reduce bias.

A third requirement in fertilizer trials over a range of soils and climate is that incomplete treatment comparisons at each site be avoided. That is, all treatments should be compared at each site. Otherwise, because of interactions with soil, climate, and other growth factors, recommendations based on average results may be seriously in error.

An experimental approach that is frequently adopted is that of conducting rather simple trials on numerous locations and pooling the results. Invariably, statistical analyses of such results will show significant site-treatment interactions which cannot be explained because of the multitude of variables that affect yield response to fertilizers. On the other hand, this is the situation that confronts farmers.

Additional requirements for valid results in fertilizer evaluation experiments are described in the following sections.

BASIC PRINCIPLES OF FERTILIZER EVALUATION

Comparative Value of Each Plant Nutrient in Fertilizers

Since fertilizers are usually applied to provide specific nutrients for crops, the primary concern in fertilizer evaluation should be to determine the comparative effectiveness of individual nutrients in each fertilizer. Most of the discussion in this manual will be concerned with this aspect of fertilizer evaluation. Black and Scott (1956) described certain aspects of the application of biological assay principles to evaluation of nutrients in fertilizers. The following requirements usually need to be met for such evaluations to be meaningful.

Standard Nutrient Sources—A commonly used fertilizer must serve as the standard. Concentrated superphosphate (CSP) has been commonly used as the standard for phosphorus (P) source comparisons, KCl or K_2SO_4 for potassium (K) sources, NH_4NO_3 for nitrogen (N) sources, etc.

Standard commercial fertilizers may have appreciable amounts of contaminants which must be considered in experiments with secondary- and micronutrients. For example, both ordinary (16%-20%) superphosphate and $(NH_4)_2SO_4$ contain large amounts of sulfur (S); most commercial superphosphates contain S and zinc (Zn) in appreciable amounts and possibly

other nutrients in trace amounts. Particular attention must be given to impurities in fertilizers used in micronutrient experiments. Otherwise, a micronutrient deficiency might not be detected because of the micronutrient being adequately supplied in other fertilizers being applied.

Multiple Rates of Application—Sufficient amounts or rates of the test nutrient should be applied to define a response curve for each source being compared. As has been pointed out in previous papers (1960a, 1961, 1962, 1967c), evaluations of nutrient source, placement, or time of application based on a single rate of application are usually not meaningful, chiefly because it usually is not possible to determine where the comparisons would fall on a complete response curve.

Adequate Yield Response—Sufficient yield response to the nutrient under test should be obtained to make source comparisons meaningful (see section on Crop Yields).

Low Experimental Error—Experimental error should be kept to a minimum by use of a suitable experimental design and good experimental techniques.

Techniques for conducting experiments with low experimental errors will not be discussed here, since they are adequately covered in the various books on experimental design and in many published articles.

Reduction of Other Growth-Limiting Factors—Other growth-limiting factors should be reduced to a minimum or eliminated. Balancing of nutrients other than the one under test, and methods for conducting soil-plant-fertilizer experiments under greenhouse conditions are described in another manual (1966).

A common type of experimental design used to determine crop needs for two or three nutrients is the 3 x 3 or 3 x 3 x 3 factorial, in which one nutrient is compared at each level of the other(s). This design is usually unsatisfactory for evaluation of the effectiveness of a nutrient from different fertilizer sources, since most of the evaluation of one nutrient is at limiting levels of other nutrients. A much better design is that of comparing each nutrient source separately at several application rates, with all other nutrients and growth factors at as near optimum levels as is possible to determine. This type of design is also satisfactory as a basis for economic analyses of the results. In contrast, the zero and one or two nonzero rate factorial designs usually have very limited use in economic analyses, since the complete response range is not adequately covered.

In summary, yield variability and response to the nutrient being evaluated are probably the two most important aspects of fertilizer evaluation. These will be discussed more fully in the next section (Crop Yields). Most of the results were obtained with P rates and sources, but the principles apply equally to other nutrients.

Product Evaluation

A simpler type of fertilizer source comparison may be termed product evaluation. This is commonly the comparison of crop response to two or more fertilizer products, possibly without regard to nutrient content. Bag-for-bag comparisons are an example. Only visual observations may be made, or yields may be measured. Disadvantages of this type of evaluation include: (a) poorly defined fertilizers are usually compared, which contain different amounts and forms of N, P, K, and other nutrients; (b) the check treatment is usually no applied fertilizer, since balancing of nutrients among products may not be possible; (c) treatments in such trials and demonstrations may not be replicated and the plot areas may be too large for accurate yield comparisons.

Product evaluation may be useful to introduce a new fertilizer product or brand of fertilizer to farmers and extension workers. However, the possibility of obtaining useful information from such trials is quite limited (see also the section on Demonstrations vs. Replicated Experiments). This is particularly true if the trials are poorly conducted, and if the comparisons are on a large strip or field basis. As a result, product evaluation *per se* has little or no place in a research program, even if replicated small-plot trials are conducted. Poorly conducted trials can and frequently do lead to erroneous conclusions.

More precise and carefully conducted experiments are sometimes carried out to compare multinutrient fertilizers, but without equalizing nutrients other than the one under test. For example, two NPK fertilizer may be compared at several rates of application. However, it is usually not possible to determine whether a yield response was due to N, P, K, or other nutrient, and the results may have little value for modern agriculture. To the writers' knowledge, no satisfactory statistical techniques have been developed to properly interpret multinutrient responses.

Other more general types of evaluation, such as physical condition and drillability as related to granulation, costs and acceptance by farmers are also important in overall fertilizer use. Fertilizer cost in relation to expected returns is a primary basis for fertilizer use. Here, low-cost formulation to reduce manufacturing costs and high analysis to reduce transportation and application costs become the primary considerations. Some possible agronomic disadvantages may be tolerated to reduce overall crop production costs. Also, liquid or suspension fertilizers might be preferred to reduce labor needs.

MEASUREMENTS USED FOR EVALUATING FERTILIZERS

Crop Yields

Yields of the crop in terms of forage, grain, fiber, or sugar are commonly used for evaluation of fertilizers in field experiments. If it is not possible to make yield measurements, then it is desirable that the yield attribute chosen be well correlated with the crop yield.

Some investigators still fail to recognize that in order for yield comparisons to be meaningful among nutrient sources, it is essential that an appreciable yield response to the applied nutrient be obtained. Thus, fertilizer treatment comparisons should always include a check treatment, or no applied nutrient, unless the yield level without applied nutrient is known with certainty. This is seldom known for agricultural soils because of variation in climatic and other yield-limiting factors.

The Nature of Yield Response to Applied Nutrients—Figure 2 shows a typical early growth response curve by maize in greenhouse pots to soluble and less-soluble N sources on a soil low in available N. Response to soluble AN is definitely curvilinear with increasing amounts of applied N, while response to granular oxamide is essentially linear. Response to the latter would undoubtedly become curvilinear at higher rates of applied N.

Figure 3 shows early growth response by maize to CSP and a less-soluble calcium ammonium pyrophosphate (Pyro-P) source on a soil extremely low in available P. Response to CSP is

essentially linear over the range of 60-240 mg of applied P, but is curvilinear over the 0- to 60-mg range. More typical responses to CSP are shown in figures 4 and 7. Response to the Pyro-P source is linear over the entire 0- to 240-mg range.

It is obvious that limiting yields of maize are not reached with the range of rates compared. These response curves are characteristic of such crops as maize forage harvested after a

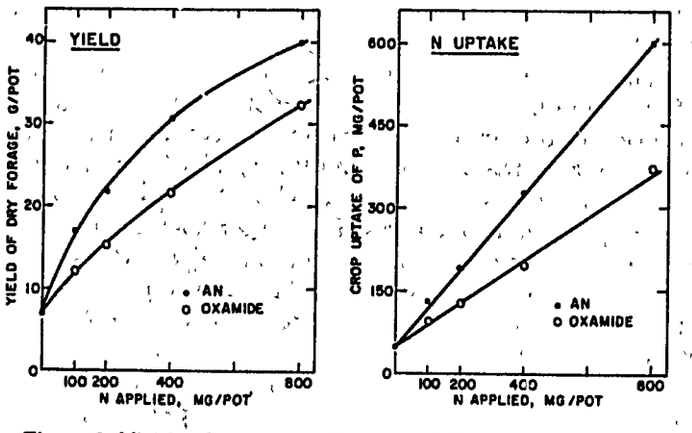


Figure 2. Yields of Dry Maize Forage and Uptake of N From –14+20 Mesh Ammonium Nitrate (AN) and Oxamide.

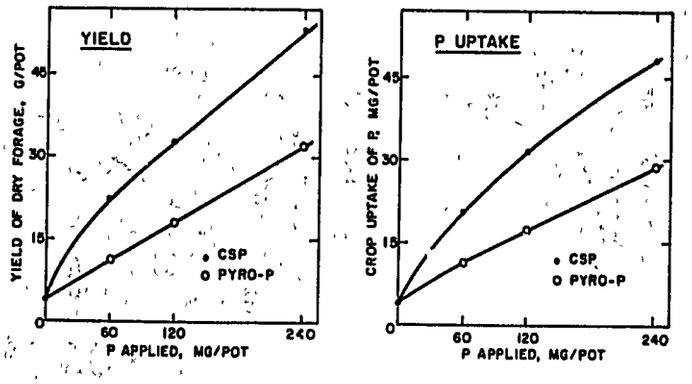


Figure 3. Yields of Dry Maize Forage and Uptake of P From –6+14 Mesh Concentrated Superphosphate (CSP) and $Ca(NH_4)_2P_2O_7 \cdot H_2O$ (Pyro-P).

few weeks of growth. The limiting yields would, of course, be much higher if growth were allowed to continue.

In figure 4 yields of oat forage harvested at the early heading stage of growth on a soil very low in available P rise rapidly with the lower rates of P applied as monocalcium phosphate (MCP) and then level off at 180-360 mg of P. Yields with the less-soluble dicalcium phosphate (DCP) rise less rapidly at lower rates of P, but approach the same limiting yield as for MCP at the higher rates. This figure illustrates the need for basing the evaluation of the two sources on results obtained on the near-linear, steeply ascending part of the response curves. The definite limiting yield of oats approaching maturity is in contrast to the indefinite limiting yields of maize at early growth stages. The definite limiting yield of oats depends on growth factors other than quality of the test nutrient. The limiting yield may be increased by better management practices involved in supplying the growth-limiting factors involved. However, with very high nutrient applications, yields may actually decrease because of toxicity, lodging, or other nutrient imbalance effects.

Figure 5 shows results from a ladino clover experiment in which the limiting yield with Florida fine phosphate rock, a P source largely insoluble in water but 15%-20% soluble in ammonium citrate solutions, is considerably lower than that obtained with CSP. Apparently the phosphate rock as the sole

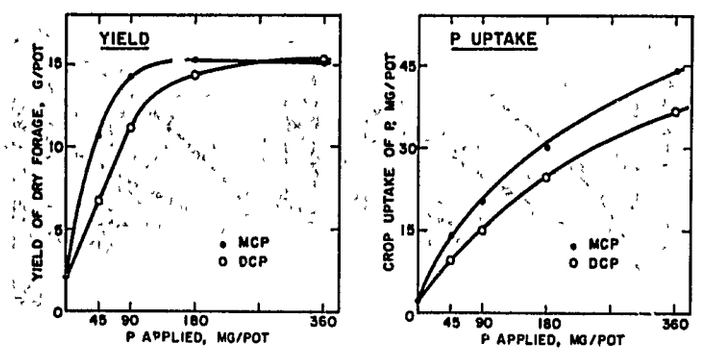
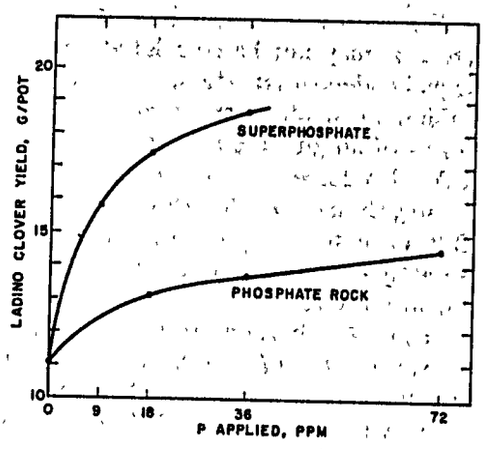


Figure 4. Yields of Dry Oat Forage and Uptake of P From Fine Monocalcium Phosphate (MCP) and Dicalcium Phosphate (DCP) on Heavily Limed Hartsells Fine Sandy Loam.

Figure 5. Mean Yields of Dry Ladino Clover Forage with Increasing Rates of P Applied as Superphosphate and Phosphate Rock on 15 Soils in a Greenhouse Pot Experiment (Ensminger *et al.*, 1967).



source of P does not supply enough P to support high yield levels of this crop. Various sources of phosphate rocks, however, have been found to differ quite widely in citrate solubility and availability of the P for crops.

Effects of Yield Variability—A commonly used formula for calculating the number of replicates necessary to measure a given difference among fertilizers is:

$$N = 8\ C.V./D \text{ in percent} \qquad [1]$$

In this formular (Patterson, 1939), N = number of replicates, C.V. (coefficient of variability) = standard error/mean x 100, and D = yield difference among fertilizers which one is attempting to measure. From this formula, it is necessary with 4 replicates to have a C.V. of 5% or less to measure a difference of 10%. With a C.V. of 10%, 8 replicates would be required, etc.

Results from analyses of variance of 433 field tests conducted in the southeastern United States on P-deficient soils to compare P sources and rates were summarized (1957a). Only 2% of the tests had a C.V. of 5% or less. In these tests with various crops, 17%-32% of the tests had C.V. in the range of 5%-10%. Thus, in only a rather small proportion of the tests, in which the treatments were replicated 3-6 times, was it possible to measure small differences among fertilizers. However, there is some question whether additional replication to measure smaller differences would have been worthwhile.

Standard errors in such experiments may increase with yield level or may not be correlated with yield level. C.V., however, usually decreased (figure 6) with yield level (1961) to a minimum of 5% in the case of experiments with maize at yield levels of about 75 bushels/acre or higher (4,620 kg of grain/ha). C.V. also decreases with increase in yields of other crops.

Magnitude of Response to the Nutrient Under Test— Response to the nutrient under test is equally important or sometimes more important than is variability in the experimental results.

The Mitscherlich response function was used to study responses in 174 tests in the southeastern United States involving rates of applied P (1960a). In a typical experiment with wheat forage, the following yields as percentages of the limiting yield were obtained: No P(Y_0)-30%; 10 kg P-78%; 20 kg P-92%; 30 kg P-98%; and 40 kg P-100%, or A. As illustrated in figure 7, the difference between the yield (Y) of the standard at the rate (R) used for other sources (assuming only one rate-10 kg) and A, determines whether it is possible to distinguish a source which is better than the standard. Similarly, the difference between the yield (Y) of the standard and the

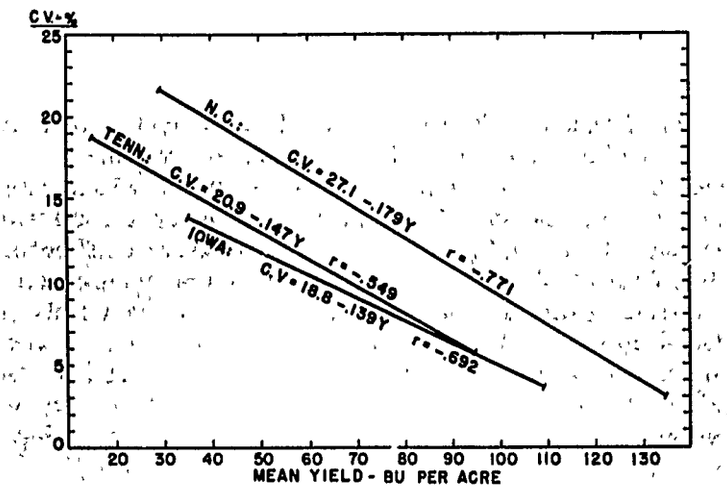
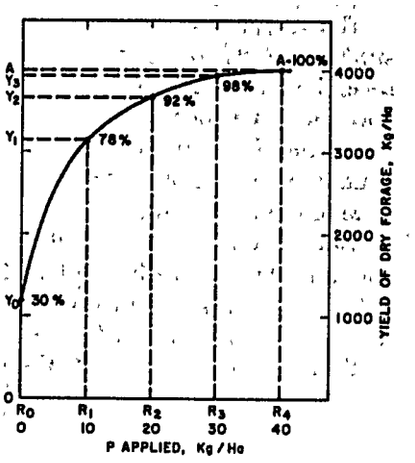


Figure 6. Relationship Between Yield of Maize Grain and C.V. in 42 Field Experiments in Iowa, 59 in North Carolina, and 57 in Tennessee.

Figure 7. Responses of Wheat Forage to Rates of Applied P in a Mississippi Field Experiment (1960).



yield without P (Y_0) determines whether it is possible to distinguish a source which is poorer than the standard but better than no P. These differences are evaluated in comparison with the standard error, least significant difference (L.S.D.) or other statistic, as determined by analyses of variance.

Average response curves were determined for 31 field tests with cotton, 41 with corn, 35 with wheat grain, and 23 with annual forage conducted in the southeastern United States (1960a). Most (80% or more) of the P deficiencies were corrected by the first 10 kg of P. Wheat forage was much more responsive to applied P than were the other crops. It was possible in only a few of the experiments to distinguish a source which might be better than CSP; and in some it was not possible, because of low response, to distinguish one which might be poorer than CSP.

A similar study was made of 124 P rate and source experiments conducted in northern and western states (1961). Results from a majority of the experiments were not meaningful because of low response to applied P. Most response was obtained with vegetable crops.

Other than for the purpose of determining the magnitude of the experimental error and relating it to yield differences among treatments, the writers have found analyses of variance of limited use in fertilizer evaluation experiments. Regression methods based on results from multirate experiments are much more useful.

The suggestion is frequently made that nutrient source studies should be made on the same plots over a period of several years. Phosphorus sources, however, react with the soil and the reaction products become more similar in availability with time. Little or no difference in response among sources can usually be measured after one or two crops.

Much direct and circumstantial evidence indicates that considerable amounts of nutrients must be taken up from both the soil and currently applied fertilizers for maximum yields. Under such high yield conditions, phosphate applications are largely to maintain high P levels in the soil. Any phosphate fertilizer which reacts with the soil seems to be satisfactory for this purpose.

Nutrient Uptake by the Crop

Nutrient uptake is usually linear over wider ranges of application rates than is crop yield. In figure 2 the uptake of N by maize is linear with 0-800 mg of applied N. These results are typical also of uptake of other nutrients such as K and S. Uptake of less mobile nutrients such as P may be linear at low application rates, but frequently is curvilinear, as shown in figures 3 and 4. A linear model is thus appropriate for interpreting the N uptake results in figure 2, but a curvilinear model should be used for the P uptake results in figures 3 and 4.

Essentially the same differences in relative effectiveness between the soluble and less-soluble N and P sources in figures 2, 3, and 4 would result from use of either yield or nutrient uptake if (a) the proper model is selected, and (b) the efficiency of the nutrient absorbed by the crop for producing dry matter is the same for both sources (within experimental error). This may be determined by plotting dry matter yields against the corresponding nutrient uptake values. If the results fall on a single smooth curve, as shown in figure 8, it may be concluded that the nutrient efficiency of the two sources is the same. If the efficiencies of the two sources are different (figure 9) because of different time of absorption or other factor, then interpretations based on dry matter yield and nutrient uptake tend to be different.

In cropping situations where there is insufficient yield response to the applied nutrient to use this measurement for evaluation, there may be considerable increase in nutrient

Figure 8. Plot of Dry Matter Yield vs. Uptake of N by Maize, Showing the Same Internal Efficiencies of the N in AN (Ammonium Nitrate) and in Oxamide.

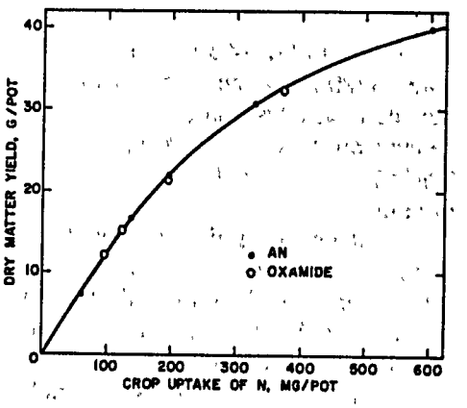
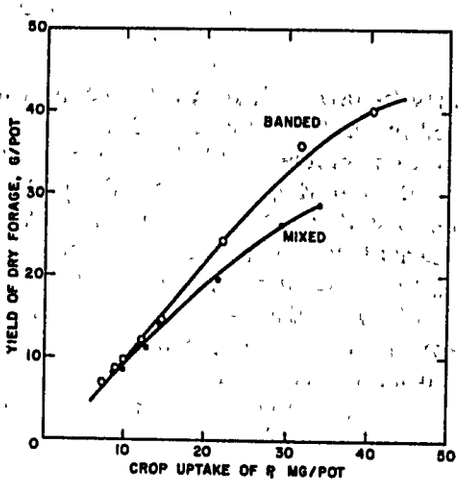


Figure 9. Yields of Dry Maize Forage vs. Uptake of P, as Affected by Placement of CSP.



uptake with amount applied. In these and other situations it may be desirable to use nutrient uptake as the basis for evaluation, since the objective may be to determine how effective various nutrient sources are for supplying nutrient to the crop. Numerous growth-limiting factors may prevent a yield response to the absorbed nutrient, thus limiting the use of yield as a valid basis for evaluation.

Uptake of Labeled Nutrient by the Crop

Certain radioisotopes such as ^{32}P, ^{35}S, and ^{65}Zn may be used to label the same nonradioactive nutrients during manufacture of fertilizers. Plants are grown in the usual manner with the labeled nutrients. At harvest the amounts of nutrient from the labeled source and from the soil are determined by appropriate methods.

Use of certain radioactive isotopes of nutrients such as N and K for crop growth experiments is not feasible because of the very short half-life of radioisotopes of these nutrients. The natural stable ^{15}N isotope of N is used for labeling in N fertilizer experiments.

A common method for evaluating the effectiveness of the labeled nutrient sources is through the calculation of A values by the method of Fried and Dean (1952) or Larsen (1952a). The formula,

$$A = \frac{R(1-Y)}{Y} \qquad [2]$$

may be used, where A is the amount of available nutrient in the soil in terms of the labeled nutrient source, R is the amount of nutrient applied, and Y is the percentage of the nutrient in the plant derived from the fertilizer. Relative effectiveness is then calculated as the inverse ratio of the A value for the test nutrient source to the A value for the standard source. This method of determining uptake of nutrient from labeled fertilizer nutrients has been termed the direct method of evaluation, as compared to the indirect methods using nonlabeled nutrient sources.

A single rate of each labeled source has been commonly used for the evaluation (Fried and Broeshart, 1967a). However, results from a recent study (1968b) indicate increases in A values with application rate of labeled nutrient under many growth situations. This may cause relative effectiveness values among nutrient sources to be different, depending on the rate selected, and especially if different rates are used for different sources. Crop recovery of the applied labeled nutrient was found to be a better basis than A values for nutrient source evaluation in a later study (1969a). In this study, crop recovery of labeled nutrient was linear over a rather wide range of application of ^{32}P, while A values were rather erratic with rate,

especially at high soil P levels. At high soil P levels, uptake of labeled P was the only suitable measurement made for P source evaluation. At a low P level, however, yield of dry matter, total uptake of P, and uptake of labeled P were equally suitable for evaluating P sources.

Thus, if evaluation experiments are carried out on soils deficient in the nutrient under test, there may be little or no advantage for labeling the nutrient sources over multiple rates of unlabeled sources. If soils are used on which little or no increase in growth or total nutrient uptake is obtained, any evaluation of nutrient sources must involve labeling. For evaluation of a natural source of P such as phosphate rock or of processed fertilizers difficult to label, the method of soil nutrient labeling has been used. This involves calculation of A values for the soil alone and for the soil plus the test sources. The difference is then assumed to be the A value for the test source. Soil labeling with carrier-free ^{32}P was found less satisfactory than fertilizer labeling for evaluation of P sources for flooded rice (1970a).

MATHEMATICAL MODELS USED TO EVALUATE NUTRIENT SOURCES

Relative Yields and Yield Increases

Before the use of regression methods illustrated below for determining availability coefficients, a single rate of applied nutrient was commonly used to evaluate different fertilizer sources of a nutrient. Relative effectiveness values were calculated from actual crop yields or yield increases over no applied nutrient.

$$\text{Relative yield (RY)} = \frac{\text{yield with test fertilizer}}{\text{yield with the standard}} \times 100 \qquad [3]$$

$$\text{Relative yield increase (RYI)} = \frac{\text{yield increase for test fertilizer}}{\text{yield increase for the standard}} \times 100 \qquad [4]$$

Both of these expressions assume that the yield response would be linear with increasing amounts of applied nutrient. However, yield response is invariably curvilinear over much of the response range, although a linear response may be obtained at low application rates.

Figure 10 (Terman, 1967c) shows the same curvilinear response of wheat forage to increasing amounts of P as superphosphate in a field experiment on a P-deficient soil as was shown in figure 7. The limiting yield (100%) was obtained with 40 units of P.

In test A (figure 10), a less-soluble P source was compared with superphosphate at a single rate of 10 units of P, on the steeply ascending portion of the complete response curve. Although the interpretation of poorer response can be made on the basis of either a linear or a curvilinear model, the effectiveness of the poorer source is over-estimated by the linear model.

In test B, however, the comparison was made at a single rate of 30 units of P. At this or higher rates of applied P, the conclusion based on any model would be that no difference in effectiveness exists between the two P sources. Thus, if a single rate of applied P is used to evaluate several sources of this nutrient, all may supply adequate P if the yields fall on the flat portion of the complete response curve. This may be true, even though the sources are shown to be quite different in availability with a more satisfactory evaluation procedure, such as using multiple rates of application of each source. It may then be concluded that both the model and the rate of application are important in comparing yields resulting from a nutrient in a test fertilizer with that in a standard fertilizer.

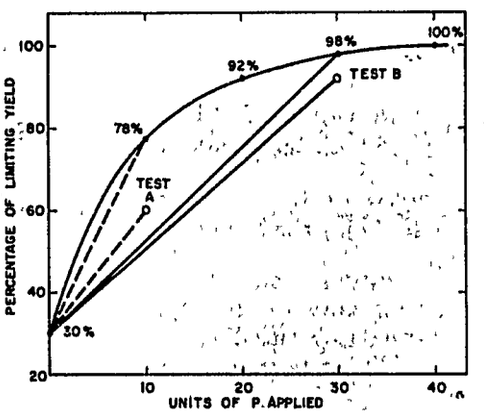
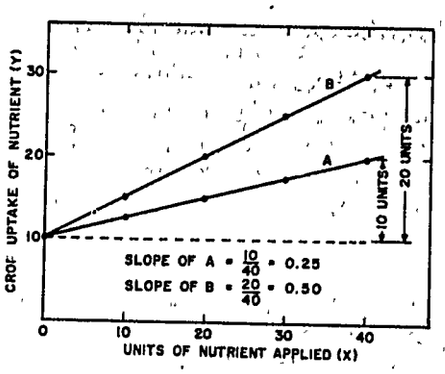


Figure 10. Response of Wheat Forage on a P-Deficient Soil to Increasing Amounts of P as Superphosphate (the Standard) and Two Single-Rate Comparisons with a Test Source.

Figure 11. Comparative Effectiveness of Nutrient Sources A and B in Terms of Linear Uptake of Applied Nutrient by the Crop. The Regression Equations are:
$Y_A = 10 + 0.25X$;
$Y_B = 10 + 0.50X$



Linear Regression Models

To compare the effectiveness of different nutrient sources based on multiple rate comparisons for each source, availability coefficient indexes (ACI) are calculated. This is true for both linear and curvilinear responses.

If the responses are linear with several amounts of applied nutrient, as is more often the case with uptake of applied N or K, the calculations are rather simple. The equation is:

$$Y = a + bx, \qquad [5]$$

in which Y is the yield or uptake, a is the Y-intercept with no applied nutrient, b is the slope, and x is the rate of applied nutrient.

Slopes (b) of the linear uptake based on the least squares fit for each source are used as the ACI values. The relative effectiveness of each source under test is then the ratio of its slope to that of the standard, as illustrated in figure 11. In this method the calculated Y-intercepts for no applied nutrient may be slightly different for each source. The following model (Engelstad, 1968) provides for a common intercept:

$$Y = a + b_1x_1 + b_2x_2 + \ldots + b_nx_n \qquad [6]$$

Standard multiple regression programs can be used for making the least squares calculations by computers. Values useful in making statistical comparisons among slopes for the different nutrient sources are usually provided on the printout. The common intercept and slope calculations may also be made on desk calculators (White *et al.*, 1956b). If neither is available, the slopes can be estimated as shown in figure 11.

Curvilinear Regression Models

Yield responses to increasing amount of applied nutrient are usually curvilinear and suitable models must be used for estimation of the coefficients.

Nutrient Equivalents. A simple method of evaluation advocated by Cooke (1956a) and others is that of comparisons among nutrient sources based on standard fertilizer equivalents.

The most effective use of this method is for experiments in which multiple rates of the standard source are compared to define the shape of the response curve, with only a single rate of other sources. This method, illustrated in figure 12, gives comparative values similar to those obtained by more complex models and calculations by computer methods described below.

Mitscherlich Models. A modified form of the Mitscherlich response function may be used, in which

$$c = \frac{1}{x}\log\frac{A-Y_o}{A-Y} \qquad [7]$$

c represents the effect factor, x = the rate of applied nutrient, A = the limiting yield with increasing amounts of applied nutrient, Y_o = the yield without applied nutrient and Y = crop yield at each rate of applied nutrient. The limiting value (A) may be estimated rather simply as the best linear fit of a plot of A-Y against x on semilog paper. Computers may be used for more precise values. Calculation of relative effectiveness based on c values for the standard and test nutrient sources is illustrated in figure 13.

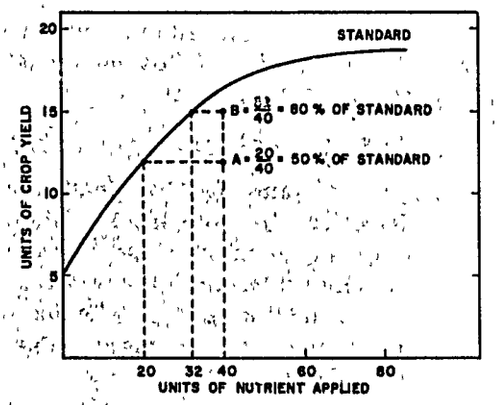
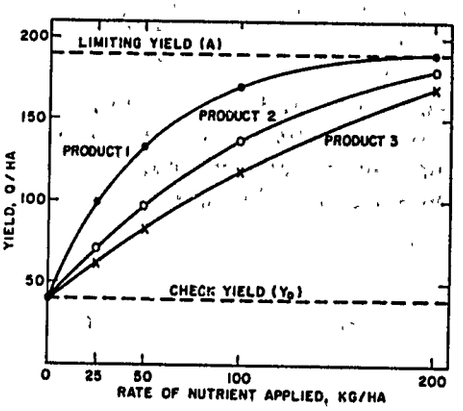


Figure 12. Estimation of Nutrient Source Effectiveness in Terms of Nutrient Equivalents of the Standard (Units of the Experimental Source Which Give the Same Yield as R Units of the Standard Source).

Figure 13. Calculation of C (Equation 7), or Availability Coefficient Indexes (ACI), Using a Mitscherlich Model: $ACI = \frac{1}{x} \log \frac{A \cdot Y_o}{A \cdot Y}$. The Ratio of the ACI Values Gives the Relative Effectiveness of the Nutrient Sources.



This simple type of Mitscherlich model, as is the case with simple linear analysis, may result in different Y-intercepts for each nutrient source. A concurrent form of the Mitscherlich model (Engelstad and Khasawneh, 1969) as follows provides a common intercept:

$$\ln(1 - \frac{Y}{A}) = a + c_1 x_1 + c_2 x_2 + \ldots + c_n x_n \qquad [8]$$

The limiting yield (A) can be estimated on semilog paper, as for the simpler model, or it can be calculated as a part of the computer program. This program also calculates values useful in statistical tests to determine which coefficients are significantly different.

Other Models

Pesek (1964) has applied the following quadratic polynomial model to curvilinear yield responses for evaluation of N sources:

$$Y = a + b_1 x_1 + b_{11} x_1^2 + b_2 x_2 + b_{22} x_2^2 + \ldots + b_i x_i + b_{ii} x_i^2, \qquad [9]$$

where Y represents yield and a the intercept; b_i and b_{ii} the required coefficients for each of the various nutrient sources compared. This model provides a common intercept, but not a common limiting yield.

Since comparison of slopes *per se* can be quite misleading in the absence of a common limiting yield, Pesek suggests that the comparison be based on responses (ΔY) at a common rate of x. The calculation would be performed as follows:

$$\frac{ACI_1}{ACI_2} = \frac{\Delta Y_1}{\Delta Y_2}, \qquad [10]$$

where ΔY_1 and ΔY_2 represent the response above the check to added nutrient. The common rate of x, as Pesek suggests, can be the economically optimum rate. For this latter calculation, see the section on Economically Optimum Rate of Nutrient.

ECONOMIC INTERPRETATIONS

In situations where the cost of nutrient in one fertilizer source is different from the cost in another source, an economic interpretation of effectiveness is desirable.

Since source comparisons involving multiple rates of application are essential for meaningful evaluation of a nutrient in different fertilizer sources, the yield results obtained may also be useful for determining the economically optimum rate of application for the crop.

Economic Effectiveness of Nutrient Sources

The relative agronomic effectiveness of two nutrient sources is given by the ratio of the respective availability coefficient index values: ACI_1/ACI_2. The relative economic effectiveness (REE) can be obtained by multiplying this ratio by the inverse ratio of the respective costs (C) per unit of nutrient in the two fertilizers:

$$REE = \frac{ACI_1}{ACI_2} \quad \frac{C_2}{C_1} \qquad [11]$$

For example, suppose that N in fertilizer 1 has a relative agronomic effectiveness of 1.0 and costs \$2.00/unit, while these values for fertilizer 2 are 1.5 and \$2.40.

REE of fertilizer 1 $= \frac{1.0}{1.5} \times \frac{2.40}{2.00} \times 100 = \frac{2.40}{3.00} = 80\%$ that of fertilizer 2.

This result indicates that fertilizer 2 is the more economic source for the set of crop-soil-fertilizer conditions under which the experiment was conducted. From additional results over a given area, a more generalized relationship might be derived.

Such calculations can be based on either the linear or the curvilinear case. For the latter, slopes can be used only when all curves approach the same limiting yield. However, where limiting yield is not constant for all sources, the calculation of REE can be more safely based on a ratio of yield increases as proposed by Pesek (1964) as described in the section entitled Other Models. The computation would be as follows:

$$REE = \frac{\Delta Y_1}{\Delta Y_2} \times \frac{C_2}{C_1} \times 100 \qquad [12]$$

where ΔY_1 and ΔY_2 represent yield increases for each source. These yield increases can best be computed at a common rate of x; this might well be the economically optimum rate as previously suggested. The procedure is given below.

Economically Optimum Rate of Nutrient

With appreciable yield response to the applied nutrient in multiple rate experiments, it is frequently desirable to calculate the economically optimum rate of application. Without appreciable response, however, the errors involved tend to be too great for meaningful estimation of the optimum rate.

Such calculations may be particularly important in countries where fertilizer is high priced relative to that of the product. In many developed countries, however, fertilizer costs are low relative to price of the product. In this case difference between the rates for optimum yield and maximum yield may be quite small.

The determination of the optimum rate of application is based on the concept of equating marginal costs to marginal returns. That is, the cost of the last unit of nutrient should be just equal to the value of the yield increase from that unit. To permit such a calculation, several (greater than 2) rates of nutrient must be used and the complete range of response should be obtained to the point where the slope decreases to essentially zero.

If a mathematical function has been fitted to the yield response curve, the calculation of the optimum rate is made fairly quickly. While several common models have been fitted to yield response curves, the quadratic will be used to illustrate the procedure:

$$y = a + bx + cx^2, \qquad [13]$$

where y and x represents units of yield and nutrient, respectively, and a the intercept. The calculation of the optimum rate is performed by equating the first derivative of y with respect to x in the above model to the inverse price ratio as follows:

$$\frac{dy}{dx} = b + 2cx; \qquad [14]$$

$$\frac{Px}{Py} = b + 2cx, \qquad [15]$$

where Px and Py represent the price per unit of nutrient and product, respectively. Solving for x in the latter relationship provides the economically optimum rate for the particular set of conditions under which the response curve was obtained.

This determination of the optimum rate can also be performed graphically. The essential features are plots of the yield curve (expressed as value per unit land area) and the accumulative cost of fertilizer as a function of rate (variable cost) as provided in figure 14. The optimum rate for this hypothetical example is that point on the abscissa where a tangent to the yield curve is parallel to the variable cost line. The optimum rate is indicated in this example by the vertical dotted line.

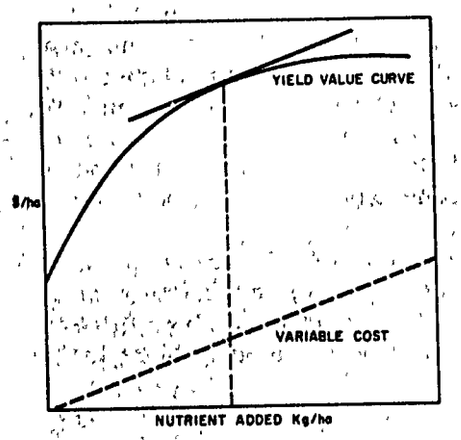


Figure 14. The Graphical Solution to Determining the Optimum Rate of Nutrient.

SPECIAL PROBLEMS IN NUTRIENT SOURCE EVALUATION

Seedling Toxicity

Two types of plant toxicity may be involved in the evaluation of new fertilizer compounds. One is positional toxicity due to concentrations of salt or ammonia with or near developing roots. Soluble N, K, and micronutrient fertilizers tend to cause more positional toxicity problems than do phosphate fertilizers. Boron in particular has a rather narrow range between deficiency and toxicity. Such toxicity may be reduced or eliminated by use of a more suitable application time, rate, or placement. A second type of damage is that due to the initial compounds or decomposition products which may be toxic, even though not concentrated near developing roots. Examples include various thiocyanates, sulfites, and phosphites, but these are not present in fertilizers except as possible contaminants. Many organic combinations of N and S are highly toxic.

A satisfactory evaluation of different fertilizers as sources of nutrients cannot usually be made if seedling toxicity is involved. The latter becomes the limiting growth factor, rather than the nutrient under test. Thus, if little is known about a new fertilizer compound, a preliminary seedling toxicity test may be desirable.

In most nutrient source evaluation experiments care must be taken to avoid appreciable concentrations of N fertilizers with crop seeds. Urea and anhydrous ammonia are particularly toxic to seedling growth. Caution must also be used with other ammonium fertilizers. Seedling toxicity tends to be more severe in coarse-textured soils and when moisture is in limited supply. Thus, soil texture in relation to rainfall and irrigation practice and soil pH are the two more important soil properties which affect crop use of N from various sources. Time of application is also important.

Leaching and Volatilization Losses of N

If attention is given to the best-known application methods, all common N sources tend to result in similar crop response on well-drained upland soils.

The main concern with most N fertilizers is to reduce losses by leaching and by volatilization from surface application and to avoid seedling toxicity. Ammonia may be lost by volatilization from surface-applied urea on both acid and alkaline soils. Severe losses as ammonia from surface-applied ammonium fertilizers usually occur only on alkaline or heavily limed acid soils. Thus for N topdressing experiments, urea or other N fertilizers subject to excessive loss by volatilization are poor standard sources. The volatile nature of anhydrous ammonia or ammonia solutions requires that they be injected into the soil to avoid volatilization losses as NH_3.

In addition to possible losses of N to the atmosphere, tie-up of ammonium N by organic matter and clay also may confuse the interpretation of yield results. In the case of slow-release N sources it is difficult to separate possible volatilization loss from the N which does not become available for the crop.

Losses of N by leaching can be eliminated in greenhouse pot studies by use of the weighing method of adding water to avoid waterlogging and the use of pots without drains. In field studies, the elimination of leaching of NO_3-N is possible only if the amount of water is regulated so that only the root zone is wetted. In humid areas this is frequently not possible, and leaching may occur at some or all seasons of the year.

Measurement of residual N from an added fertilizer is difficult because the amount added is usually very small in relation to the total amount of N already present in the soil. Labeling the fertilizer with ^{15}N isotope is at least a partial solution to the sampling and analytical problems involved.

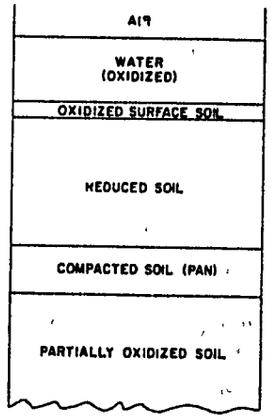
Flooded Rice Culture

Nitrogen—In a flooded rice paddy the floodwater and a thin layer of surface soil (figure 15) remain in a partially oxidized condition. Soon after flooding, however, a reduced soil zone develops below the soil surface. If NO_3-N is present in the soil, this N is lost from the reduced soil layer following flooding as follows:

$$NO_3 \xrightarrow{\text{Denitrification}} N_2 \text{ or } N_2O \uparrow$$

If NH_4-N is formed from soil organic matter or is placed below the soil surface and flooded before nitrification occurs, the NH_4-N is stable and remains there for crop use.

Figure 15. A Section Through a Typical Flooded Paddy Soil, Showing Oxidized and Reduced Soil Layers. In Soils Where the Pan of Low Permeability is Absent, Movement of Water and Nutrients Beyond the Root Zone May Be Excessive.



As the rice crop develops, a mat of roots forms at or near the soil surface. After this occurs and the crop is absorbing N rapidly, applying either NH_4-N or NO_3-N as a topdressing to the floodwater may give satisfactory results.

In a rice soil in which a compact zone is not present, leaching of NO_3-N not already lost by denitrification may occur. Also, unhydrolyzed urea may be leached beyond the root zone, since urea is only weakly held by the soil.

Thus, placement of N, time of application, and nature of the soil can all be important in determining the effectiveness of various N sources for paddy rice.

Phosphorus—As a result of the reducing conditions which develop after flooding a soil, availability of the soil P for rice usually increases (Patrick and Mahapatra, 1968a). As a result, soils which may exhibit a marked response by maize and other upland crops to applied P may show a much smaller response or even no response at all to applied P by rice after flooding. Thus, Terman *et al.* (1970) showed that different P sources could be evaluated satisfactorily for rice only on a soil testing very low in acid-soluble P. Rice grown on many alluvial and other soils throughout the world shows little or no yield response to applied P fertilizers. On such soils any water-soluble or citrate-soluble P source may be satisfactory to maintain an adequate soil P level for paddy rice.

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Design and Sample Calculations For Specific Types of Field Experiments

The following general procedure is suggested for experiments to be conducted:

1. Write a proposal for the experiment, including title, background, objectives and detailed procedure.
2. Prepare an experimental outline showing the proposed list of treatments and plot layout. Both randomization and replication of each treatment are essential.
3. Draw up a work plan with each step outlined in detail. This is especially necessary if several technicians are involved in various phases of the experiment.
4. Prepare weight sheets for all experimental and other fertilizers to be applied per plot.
5. Make calculations and write directions for preparation of any special fertilizers, soil treatment, crop handling, etc.
6. Select a soil area for the experiment which is as uniform as possible and which is expected to result in a yield response by the crop to the nutrient under test. This should be established in a preliminary test if possible.

Some additional factors to be considered include:

1. *Plot size.* This can vary with crop, site, and the nature of cultural operations. In the following examples, plots 3 x 6 m., giving 18 m^2, or 0.0018 ha were used for the calculations.
2. *Nutrient rates.* Rate of nutrients per hectare should fit the local crop response patterns. At least two nonzero rates of nutrient from each source, as well as a zero treatment for the nutrient under test should be included. The nutrient increments might be increased arithmetically, i.e., 0, 50, 100, and 150 kg/ha or geometrically, i.e., 0, 50, 100, and 200 kg/ha. The actual rates selected should cover the expected yield response range. This is particularly important for estimation of the economically optimum application rate.
3. *Experimental design.* A randomized complete block design with 4 replicates is usually adequate. A randomized split-plot design can be used if the objective is to compare one factor

(e.g., nutrient source) more precisely than a second factor (e.g., rate of nutrient). Partially confounded incomplete block designs are not recommended for nutrient source evaluation.

4. *Statistical analyses.* Analysis of variance should be performed as a first step to determine whether statistical differences among rates and sources exist. If such differences are found, regression analyses as described by Engelstad (1968) or Engelstad and Khasawneh (1969) should be carried out.

The following examples of experiments and the necessary calculations of amounts of fertilizers to apply vary from simple to more complex to illustrate certain nutrient balancing problems which may arise.

Example 1

Title: Effectiveness of P in phosphate rocks varying in citrate solubility.

This example illustrates a simple type of experiment with no special problems. The objective is to evaluate the P in the following sources for a crop.

P source	Total P_2O_5, %	Total P, %	AOAC-available P, % of Total
Concentrated superphosphate (CSP), Granular (-6+9 mesh)	49.7	21.7	98
Phosphate rock (PR-1), -200 mesh	34.7	15.1	1
Phosphate rock (PR-2), -200 mesh	32.7	14.3	16
Phosphate rock (PR-3), -200 mesh	29.9	13.0	26

(4 P sources x 3 P rates + no P) x 4 replicates = 52 plots (39 with 3 replicates)

If an additional objective is to measure residual effects during a second crop, then 4 additional no-P plots should be included, on which to make a fresh application of CSP as the standard for the second crop yields.

The phosphate treatments are given in table A-1. Uniform application of lime, N, K, S, and micronutrients over the plot

area should be made as needed to provide adequate levels of these nutrients for high crop yields.

Table A-1. Treatments and Rates of P to Apply (Example 1)

P source and total P content, %	Treatment nos.	P applied, Kg/ha	P applied, g/plot	Fertilizer weight g/plot
CSP, 21.7%	1	20	36	166
	2	40	72	332
	3	80	108	498
PR-1, 15.1%	4	20	36	238
	5	40	72	476
	6	80	108	714
PR-2, 14.3%	7	20	36	252
	8	40	72	504
	9	80	108	756
PR-3, 13.0%	10	20	36	277
	11	40	72	554
	12	80	108	831
Check (no P)	13	0	0	0

Example 2

Title: Effectiveness of P in P and NP sources.

The -6+9 mesh granular fertilizers to be compared as sources of P are as follows:

P source	Total N, %	Total P_2O_5, %	Total P, %	Water-soluble P, % of total
Concentrated superphosphate (CSP, 0-49-0)	–	49.7	21.7	88
Monoammonium phosphate (MAP, 12-61-0)	12.2	61.6	26.9	100
Urea ammonium phosphate (UAP, 29-29-0)	29.9	29.4	12.8	100
Nitric phosphate (NP, 20-20-0)	20.0	21.3	9.3	54

To have a valid comparison of the effectiveness of the P in these fertilizers, it is necessary to supplement the CSP and MAP with N to equalize the N applied among the four sources. The N can be supplied as ammonium nitrate, etc., for upland crops but ammonium sulfate or urea would be preferred for paddy rice.

Fertilizer treatments and rates of N as urea and of P to apply are shown in table A-2.

Another complicating factor in relation to evaluation of these P sources for paddy rice is that about half of the N in NP (20-20-0) is in the NO_3-N form and half as NH_4-N. If this fertilizer is incorporated into the soil before or after flooding, most or all of the NO_3-N will be lost to the air through denitrification. In this case the NP should probably be supplemented with additional N as urea to compensate for this loss.

If ammonium sulfate (20.5% N and 23.4% S) is used for equalization of the N among P sources, then a variable amount of S as the sulfate is also applied. This could possibly affect the P evaluation results, especially on a soil low in S. The amount of S could be then equalized with finely ground gypsum ($CaSO_4 \cdot 2H_2O$, 18.6% S). Equalization of the S with gypsum would cause a variable amount of Ca to be applied, which is also true among the P sources. However, this would be of little importance in an adequately limed soil.

Example 3

Title: Effectiveness of N in N and NP fertilizers.

The -6+9 mesh granular fertilizers to be compared as sources of N are as follows:

N source	Total N, %	Total P_2O_5, %	Total P, %
Monoammonium phosphate (MAP, 12-61-0)	12.2	61.6	26.9
Urea ammonium phosphate (UAP, 29-29-0)	29.9	29.4	12.8
Ammonium sulfate (AS, 20.5-0-0-23.4% S)	20.5	–	–
Sulfur-coated urea (SCU, 35-0-0-21.0% S)	35.0	–	–

For a valid comparison of the effectiveness of N in these fertilizers, it is necessary to supplement the UAP, AS, and SCU with P to equalize the P applied among the four N sources. Fertilizer treatments and rates of P as CSP and of N to apply are shown in table A-3. CSP (or triple superphosphate) is selected for equalization of the P because it is largely water soluble (as is the P in MAP and UAP) and is low in S.

The N treatments also supply a variable amount of S, which may also interfere with a valid evaluation of the fertilizers as N sources. This may be at least partially corrected by additions of finely ground gypsum, as shown in table A-3. However, it is not possible to estimate the rate of oxidation of the S in SCU to the sulfate. This has been found to be rather slow especially in flooded soils.

As in Example 2, variable amounts of Ca are supplied by the CSP and gypsum additions. Again, these would not be expected to interfere with the N source evaluation in adequately limed soils.

Table A-2. Treatments and Rates of P and N to Apply (Example 2)

P source and total P content, %	Treatment nos.	P applied, Kg/ha	P applied, g/plot	Fertilizer weight, g/plot	N applied with P, g/plot	N applied for equalization[a] N, g/plot	N applied for equalization[a] As 46% urea, g/plot
CSP, 21.7%	1	10	18	83	0	168	365
	2	20	36	166	0	168	365
	3	40	72	332	0	168	365
MAP, 26.9%	4	10	18	67	8	160	348
	5	20	36	134	16	152	330
	6	40	72	268	33	135	293
UAP, 12.8%	7	10	18	141	42	126	274
	8	20	36	282	84	84	233
	9	40	72	563	168	0	0
NP, 9.3%	10	10	18	194	39	129	280
	11	20	36	387	78	90	196
	12	40	72	774	155	13	28
Check (no P)	13	0	0	0	0	168	365

[a]Equalization to 93 Kg of N/ha, the amount supplied by the highest rate of UAP.

Table A-3. Treatments and Rates of N, P and S to Apply (Example 3)

N source and total N content, %	Treatment nos.	N applied, Kg/ha	N applied, g/plot	Fertilizer weight, g/plot	P applied with N, g/plot	P applied for equalization[a]		S applied with N, g/plot	S applied for equalization[b]	
						P g/plot	As CSP, g/plot		S, g/plot	Gypsum g/plot
MAP, 12.2%	1	30	54	443	119	238	1097	0	185	995
	2	60	108	885	238	119	548	0	185	995
	3	90	162	1328	357	0	0	0	185	995
UAP, 29.9%	4	30	54	181	23	334	1539	0	185	995
	5	60	108	361	46	311	1433	0	185	995
	6	90	162	542	69	288	1327	0	185	995
AS, 20.5%	7	30	54	263	0	357	1645	62	123	661
	8	60	108	527	0	357	1645	123	62	333
	9	90	162	790	0	357	1645	185	0	0
SCU, 35.0%	10	30	54	154	0	357	1645	32	153	822
	11	60	108	309	0	357	1645	65	120	645
	12	90	162	463	0	357	1645	97	88	473
Check (no N)	13	0	0	0	0	357	1645	0	185	995

[a]Equalization to 198 Kg of P/ha, the amount supplied by the highest rate of MAP.
[b]Equalization to 103 Kg of S/ha, the amount supplied by the highest rate of AS.

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