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SOIL NITROGEN

SUPPLY PROCESSES AND CROP REQUIREMENTS

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16. Abstracts

Nitrogen use in modern agriculture has increased greatly with the growth of population and in turn the need for increased food production. Of all the soil elements essential for plant growth, nitrogen is the most likely to limit crop growth. Attention is focussed on some of the principles affecting nitrogen availability and utilization which provide for maximum efficiency in the production of cereal crops. In forecasting fertilizer nitrogen needs, several use factors are collectively evaluated. Crop requirements are determined first. The kind of crop, expected yield, amount of nitrogen absorbed and used by the plants at the projected yield level. Expected yield levels depend mostly on soil properties and climatic factors. The amount of nitrogen expected from the soil and natural resources are assessed through mineralization, biological fixation, and additions from rainfall. An evaluation of all these processes are obtained by measuring the yield of a crop when no nitrogen fertilizer has been applied. Several soil, crop, and climatic factors determine plant use of available soil nitrogen. The extent to which these factors modify and/or regulate crop use of available nitrogen plays a key role in the formulation of good nitrogen addition practices. Finally, fertilizer needs for future crops are determined by assessing plant needs, use and loss functions, and supply processes. Most of the knowledge regarding nitrogen comes from research done in temperate environments. However, the fundamentals are applicable to all regions of the world.

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SOIL NITROGEN

SUPPLY PROCESSES AND CROP REQUIREMENTS

by

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FOREWORD

In his talk entitled, "World Food-Population Problem and Overview" that was presented before the Association of Southern Agricultural Workers in February, 1969, the late Dr. W. M. Myers stated:

"Events of the last two or three years indicate that we can, indeed, increase food production rapidly enough to close the food gap and to keep up, for another two or three decades and perhaps longer, with food demand increases resulting from population growth and economic development; that we can buy time for programs to bring about population stabilization if we move forward on both the food and population fronts in the developing and the developed countries with sufficient vigor. The question is not *can we* but *will we*?"

There is no question but that soil fertility has to play a key role in increasing crop production in almost all soils of the world, either those currently under cultivation or those to be brought under cultivation. The yield potential of currently available crop varieties and improved cultural practices focuses the "spot light" on soil fertility. The relatively low yields which many soils can sustain are no longer "enough" to supply the world needs.

Of the elements that are essential for plant growth which are obtained from soil, nitrogen is most likely to limit crop growth. Factors affecting the release and availability of nitrogen in soils are somewhat different than for the other essential elements since nitrogen is found in the organic fraction. Nevertheless, the soil processes controlling nitrogen availability will be similar for soils of developing countries as well as developed countries. Also the principles should hold for tropical conditions as well as temperate regions.

Adaptive research, of course, is needed for specific soils in specific climatic areas and for specific crops. It is the purpose of this bulletin to present some of the principles affecting nitrogen availability and utilization which will provide for maximum efficiency of fertilizer nitrogen in production of cereal crops which are staples in the diet of many developing countries.

Dr. J. W. Fitts, Director
International Program on
Soil Fertility Evaluation and Improvement

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I. NITROGEN - ITS NEED IN MODERN AGRICULTURE

Nitrogen use in the production of crop plants has markedly increased in the last decade as the human population has increased and as the world has moved steadily into this technical and mechanical age. This increased need for and use of nitrogen has resulted because of: 1) the increased demand for food and other agricultural crops; 2) an improved understanding of soil fertility processes and concomitant improvement in soil management practices; 3) better quality and more productive crops; 4) the widespread availability and lower costs of nitrogen fertilizer materials; and, 5) improved technology to till the land and to harvest and handle the crops. Furthermore, the demand for ever larger quantities of better quality food by a rapidly expanding population is certain to require progressively larger increases in nitrogen use in the near future.

Nitrogen fertilizer has been used principally in the production of cultivated food crops although there is an expanding interest in its application to forest lands and grazing areas. As food production in the world is increased more land areas will be employed for food crops and greater productivity per unit of cultivated land will be required. The latter will pose the greater challange to research workers and to farm advisors in the efficient use of fertilizer nitrogen.

There exists a very extensive scientific literature on soil and fertilizer nitrogen. Technical reviews and evaluations have been made only on a few segments of the broad subject. The chief purposes of the present discussion are to provide an orderly perspective of the whole of the nitrogen picture, to indicate areas which need research attention, and to outline systems for using current knowledge in appraisals of nitrogen fertilizer needs in specific soil and cropping situations.

Most of the knowledge about nitrogen came from research conducted in temperate environments. However, the fundamentals of this

research knowledge have application in all regions of the world. There are numerous reasons to conclude that nontemperate regions differ from the temperate largely in climatic environments and that fundamental principles apply equally well in all regions when adequate consideration is given to environmental factors. The reactions and transformations of nitrogen in the soil are largely biological as also are the absorption and use processes in crop plants. There should be consistency in these processes in all crop-growing regions of the world. Consequently, the use and application of knowledge should be universal and general.

The literature consulted was too large to cite individually. Where the author considered items of information to be common knowledge, no text citations are made. In instances where evaluations of the data from a number of publications have been made, the author has drawn conclusions and listed the sources as a group in the literature section. In other instances, literature citations are made in the conventional way.

II. INEFFICIENT NITROGEN USE BY CROPS IS A MAJOR CONCERN

Nitrogen use by crops has been inefficient (Allison, 1955; Viets, 1960). Several surveys estimate plant uptake to be about 50 percent of the soluble or so called "available nitrogen." Moreover, nitrogen coming from natural processes (soil organic matter) has not been more efficiently used than that added as fertilizer (Russell and Voelcker, 1936). Much greater crop use of available nitrogen appears possible. This should be achieved through judicious soil and crop management.

There are several important reasons why proper rates of fertilizer nitrogen should be made and proper addition practices followed. Of major significance is that efficient use of nitrogen results in greater crop yield and quality per unit of land and at less unit cost of production. This means more profits to the farmer. To achieve this end, sufficient but not excessive amounts of nitrogen must be applied in each instance.

Excessive and indiscriminate applications of nitrogen fertilizers are sometimes practiced. The arguments for the practice are that inorganic nitrogen sources are cheap and high nitrogen applications economically insure high yields of crops. In such instances high rates of nitrogen probably compensate to some extent for poor addition practices or for some other limiting factors in production which might be better overcome by other means. Such excessive uses of fertilizer nitrogen creates ill effects other than those reflected in profits. They can, and often do, impair crop quality and they intensify the ground water and stream pollution problems.

Farmers and farm advisors find it necessary to anticipate soil and crop needs for fertilizers and to forecast in advance of planting the probable quantities of addition and conditions of application of plant nutrient elements. The problems we face are how best to make these forecasts. What kinds of information are needed? For the primary and some secondary elements, other than nitrogen, this forecasting information can be obtained largely

by fertility analyses of a soil sample. In some instances appropriate analyses for soil nitrogen are helpful. However, research experience has shown some fundamental differences between nitrogen and most of the other plant nutrients. The testing methodology for the latter elements is usually inadequate for nitrogen. On the other hand, general information on soil site, crop, climate, and management is helpful in both systems. Let us now consider the problems and soil processes of nitrogen.

III. THE PROCESSES AND PROBLEMS IN PERSPECTIVE

For predictive purposes for nitrogen fertilization, at any soil site and for any crop, three general factors need evaluation. These factors are: 1) the net contributions of the natural supply processes as reflected in the yield of a crop where no nitrogen fertilizer has been applied (the traditional yield); 2) the maximum productive capacity of a soil site as reflected in the yield of a crop when all management factors are near optimum including adequate nitrogen (the standard yield); and 3) the general yield response function from added increments of nitrogen when other production factors are not limiting (nitrogen use efficiency). Each of these factors vary with crop, with soil site, with season, and with management. Moreover, all systems for assessing the needs for nitrogen fertilizer make evaluations of some or all of these factors. Several nitrogen transformation and use processes are involved in determining the magnitude and importance of each factor. The processes involved in each instance are shown in Figure 1.

The supply and loss processes determine the net available nitrogen. The loss channels and plant absorption process determine the efficiency of plant use. The nature and yield of the crop determine the total need. Because plant uptake processes are not totally efficient and because some nitrogen may escape from the soil system, the available supply must always exceed crop use.

These supply, loss, and use processes are clearly reflected and partly evaluated in fertilizer response experiments (Figure 2). The magnitude of the yield without nitrogen fertilizer, 4 tons/ha (Figure 2-A) is an evaluation of the net capacity of the natural supply processes including any nitrogen carried over from a previous crop and that coming to the plot in irrigation water. The plateau zone on the response curve measures the production potential of the soil, crop, climate, and management situation of the

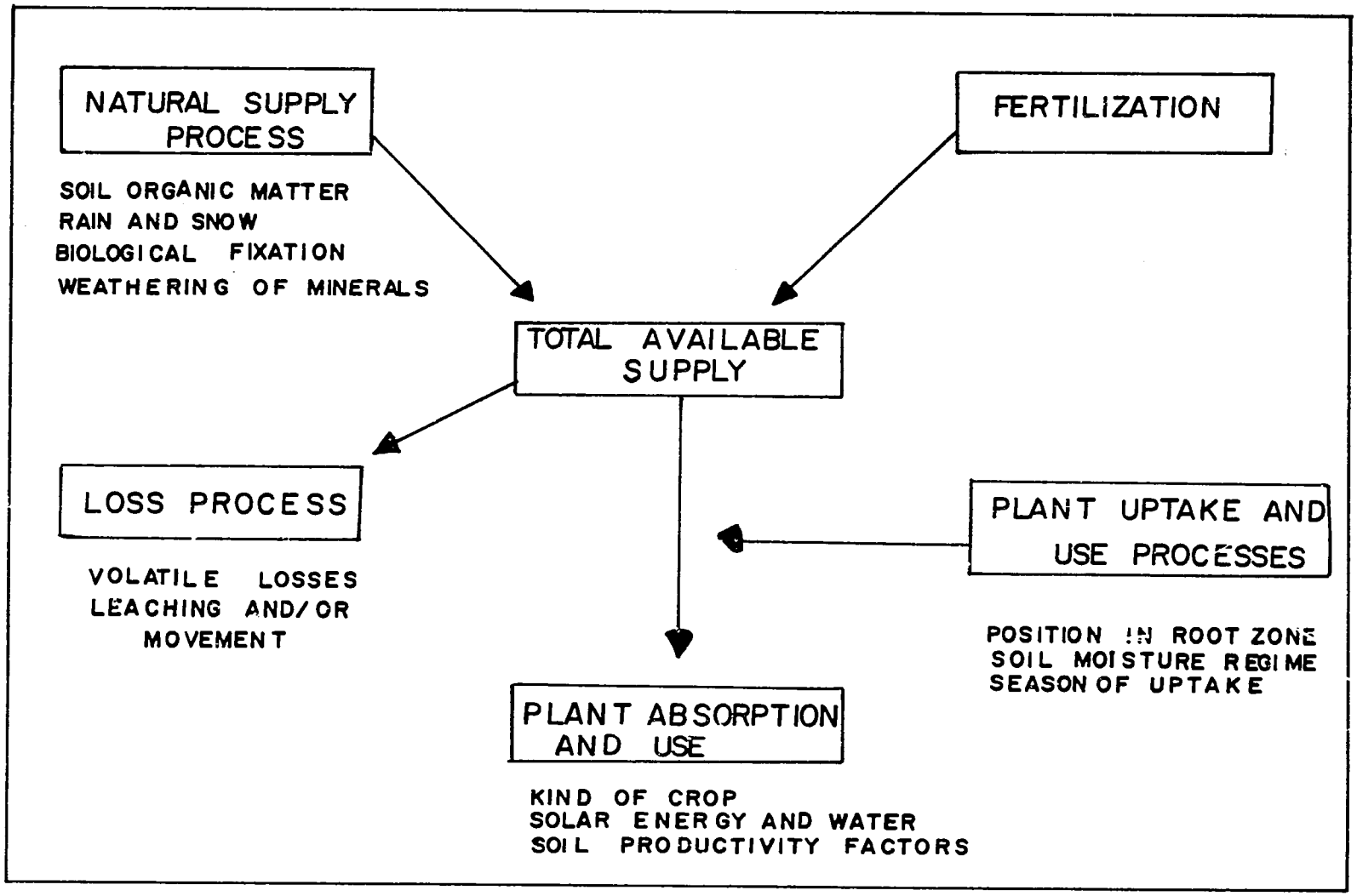

Figure 1. A perspective view of soil nitrogen supply, loss, and use processes.

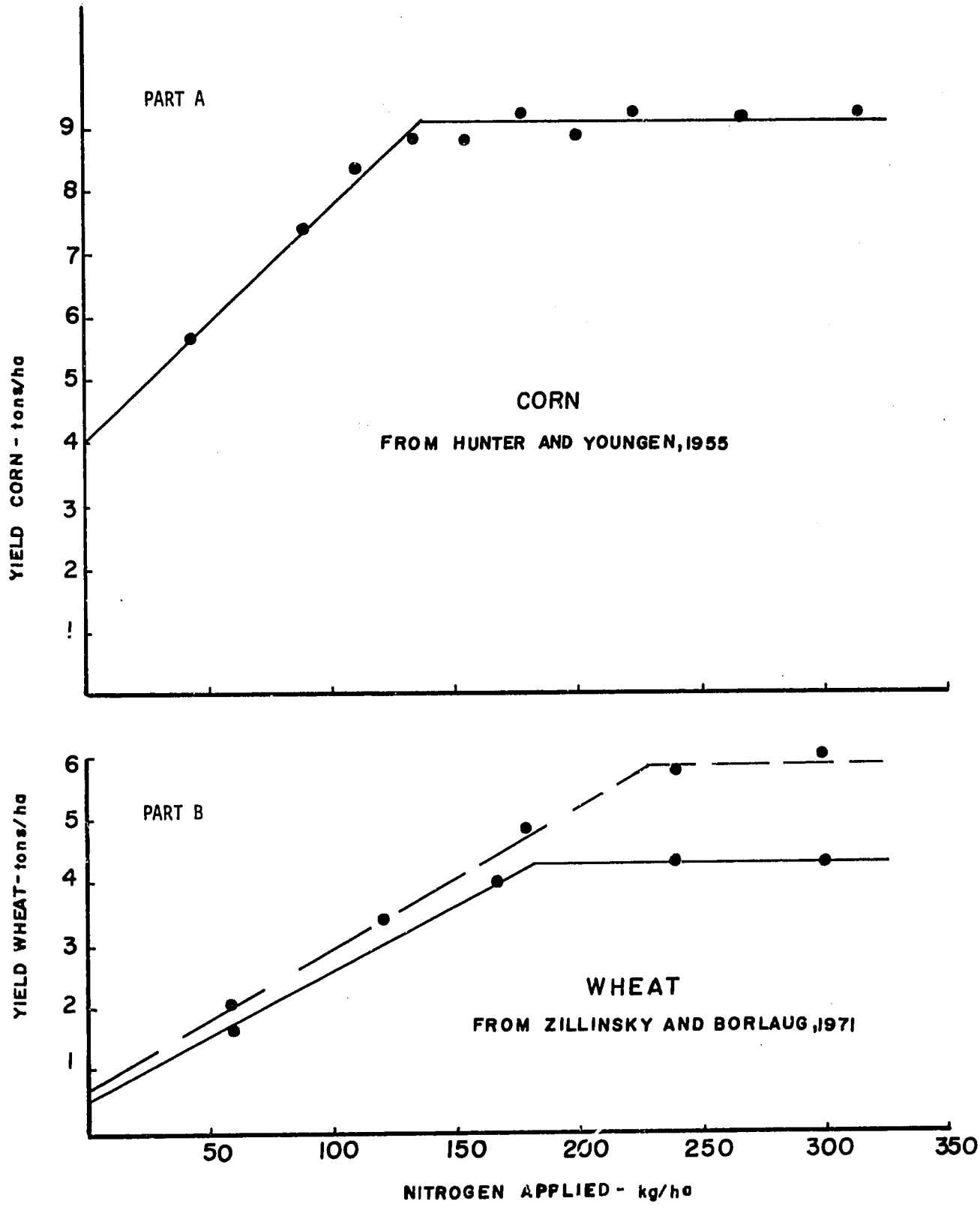

Figure 2. Graphs of field response data reflect soil supply process, crop needs, and use efficiencies.

particular field in the course of a specific season. The slope of the response part of the curve (rectilinear functions) measures the efficiency of the use of nitrogen by corn. In terms of processes the efficiency of use is controlled by the loss and plant uptake mechanisms. Figure 1 depicts the processes and the relationships of these processes to crop needs and to fertilization. Figure 2 provides an outline of the manner in which groups of processes may be quantitatively evaluated in field experimentation.

In forecasting fertilizer nitrogen needs, several use factors must be collectively evaluated. The first step is to determine crop use requirements. This involves a knowledge of the kind of crop, the expected yield, and the nitrogen absorbed and used by the plants at the projected yield level. The expected yield levels in all instances are strongly influenced by soil properties and climatic factors.

The second step is to ascertain the quantity of nitrogen which can be expected from the soil and from natural supply processes. These processes include soil mineralization, biological fixation, and additions from rainfall.

Mineralization from soil organic matter is generally the most important of these processes. Biological fixation can be large if legume culture is involved. Rainfall sources are generally small and variable.

Soil test procedures (laboratory) largely reflect mineralization of organic nitrogen or accumulations of inorganic nitrogen in the soil. They do not measure biological fixation nor do they reflect the modifying influences of crop residues. By correlation procedures for specific soil and crop situations, soil tests for nitrogen can be used to forecast nitrogen fertilizer needs. Test procedures will be considered in detail in Section VII.

A collective evaluation of the integrated influence of all of the natural processes can best be obtained by measuring the yield of a crop when no nitrogen fertilizer has been applied.

The third step is to evaluate the efficiency of plant use of available soil nitrogen. Several soil, crop, and climate related factors are involved. A knowledge of these factors and the extent to which they modify and/or regulate crop use of available nitrogen is essential to the formulation of good nitrogen addition practices. A reflection of their collective influence can be seen in crop yield response functions under field conditions.

The fourth and final step is to determine the fertilizer needs of a future crop by an integrated evaluation of plant needs, use and loss functions, and supply processes. This is frequently done by the trial method of field experimentation in which the minimum nitrogen addition for near maximum yield is measured in field plots. However, the most efficient and useful procedures have employed a knowledge of the several important supply and use factors in designing and evaluating yield trials and in determining the seasonal and total needs for nitrogen.

The discussion sequence in this bulletin will follow the order of topics outlined on page 8. Crop use and need for nitrogen in production will be examined initially, followed by an appraisal of natural supply processes. Use efficiency of nitrogen in crop production will then be reviewed and evaluated. Finally, a basic system will be outlined for predicting fertilizer nitrogen needs for the cereals. The same principles can be employed for other crops if plant uptake and nitrogen use efficiency information is available.

IV. CROP USE AND CROP NEED FOR NITROGEN

Use of Nitrogen by Crops

Nitrogen use by corn (*Zea mays*), wheat (*Triticum aestivum*), and rice (*Oryza sativa*) will be employed as illustrations. These crops are collectively the principal staple food crops for human consumption in most sections of the world. Moreover, since numerous fertilizer experiments have been conducted with cereals, research information concerning them are relatively more available than for other crops. The data will illustrate the crop use of nitrogen at various yield levels.

Most of the nitrogen used by cereals is contained in the aboveground parts -- the grain and the stover or straw. However, a sizeable quantity is also contained in the underground parts -- the harvestable roots and the organic debris arising from and associated with the roots in the rhizosphere (rhizodeposition). Much data are available on the yield and nitrogen composition of the grain. Some scattered information is available on the yield and composition of the aboveground nongrain parts. Only a little information has been found on the yield and composition of the below ground parts.[1/]

All nitrogen use estimates have been related to yield of grain. Such types of summarization required establishing relationships between: 1) yield of grain and yield of stover or straw; 2) yield of stover or straw and yield of roots; 3) yield of roots and yield of detached organic debris in soil (rhizodeposition); 4) yield of grain and nitrogen content of grain; 5) yield of stover or straw and nitrogen content of stover and straw; and 6) nitrogen content of stover and straw and nitrogen content of roots.

[1/] The references consulted are listed for each crop in the literature section.

A survey of scattered root data led the author to use the generalization that roots were about 22 percent of the weight of the tops (stover) for corn and contained nitrogen equal to about 16.5 percent of the quantity of nitrogen in the stover.

Only one publication (Shammot et al., 1968) gives information on the extent of rhizodeposition. The quantity of this material was estimated at 30 percent of the root weight and to contain about 40 percent as much nitrogen as the roots. The roots and associated detached organic debris, therefore, were estimated to contain about 25 percent as much nitrogen as the stover.

The nitrogen content (percent composition) of both the grain and stover tended to increase with increase in grain yield. There were a few exceptions to this generalization, e.g., the nitrogen percentage of stunted or nutrient starved plants. Corn grain at the lower yield levels where nitrogen was limiting had nitrogen contents only slightly above 1 percent. At higher yields and under good, well balanced nutrient conditions, the reported nitrogen contents were as high as 1.6 to 1.7 percent.

Corn stover varied from as low as 0.5 percent under poor conditions of nitrogen nutrition to as high as 1.4 percent where nitrogen was available in abundance and where uptake by the plant probably was in excess of metabolic needs.

It is of interest that in cereal production there appears to be a minimum stover or straw production for each level of grain yield. Or, in other words, a given unit production of nongrain plant substance is required to produce a specified yield of grain. On the other hand a number of production factors may result in the production of stover or straw without the concomitant production of grain. To avoid abnormal production situations, only data were used where the crop had responded to nitrogen and where other production factors were considered normal.

In an evaluation of nitrogen use by wheat the same general procedures were employed as were used for corn. Straw yields in relation to grain yields varied between wide limits. However, high straw yields tended to be low in nitrogen. When data on the quantities of nitrogen in straw were related to yield of grain, a consistent relationship was observed.

Scattered data indicated that root yields averaged about 10 to 12 percent of the straw yields. Rhizodeposition was again considered to account for a quantity of nitrogen equivalent to about 50 percent of that in the roots. As a working generalization, the roots and associated organic debris were considered to contain nitrogen equal to 16 percent of that in the straw.

Nitrogen contents of wheat products varied between wide limits. Grain percentages ranged from as low as 1.5 to as high as 3.0 percent. The data showed straw nitrogen contents as low as 0.2 percent and in some instances greater than 1.0 percent.

Rice grain (brown rice) contained from 1.2 to 1.6 percent nitrogen while the straw had from about 0.4 to 0.9 percent nitrogen. The scattered information indicated that roots were similar to straw in nitrogen content. An evaluation of the composition and yield data on the several plant parts of rice led to the conclusion that the quantities of nitrogen contained in roots and associated organic debris were equivalent to about 16 percent of the quantities of nitrogen in the straw. From data on straw and grain yield and nitrogen composition, a general relationship was established between grain yield (brown rice) and the nitrogen contained in the several plant parts.

Table 1 summarizes the general magnitudes of nitrogen use by cereal crops as related to grain yield levels. Graphic summaries are given in Figure 3. The tabulated summaries are the author's evaluations of extensive and diverse data on cereal yields and composition. Included are data from both temperate and tropical regions. Owing to the fragmentary nature of much of the primary data, confidence limits were not established.

Table 1. Nitrogen use by corn, wheat, and rice in relation to yield of grain

Grain yield	Nitrogen in plant parts								
	Corn			Wheat			Rice		
	Grain	Stover and roots	Total	Grain	Straw and roots	Total	Grain	Straw and roots	Total
T/ha	kg/ha								
0.5				9	5	14			
1.0	11	11	22	20	10	30	12	10	22
1.5				32	15	47			
2.0	23	18	41	45	21	65	25	15	40
2.5				59	27	85			
3.0	35	27	62	74	34	108	38	21	59
3.5				90	42	132			
4.0	48	37	85	106	52	158	52	28	80
4.5				123	64	187			
5.0	64	48	112	140	78	218	66	36	102
5.5				156	94	250			
6.0	80	60	140	174	111	285	80	45	125
6.5									
7.0	97	72	169				95	55	150
7.5									
8.0	114	86	200				110	65	175
8.5									
9.0	131	98	229				126	75	201
9.5									
10.0	147	112	259				142	86	268
11.0	164	125	289						
12.0	179	139	318						
13.0	194	153	347						
14.0	209	167	376						

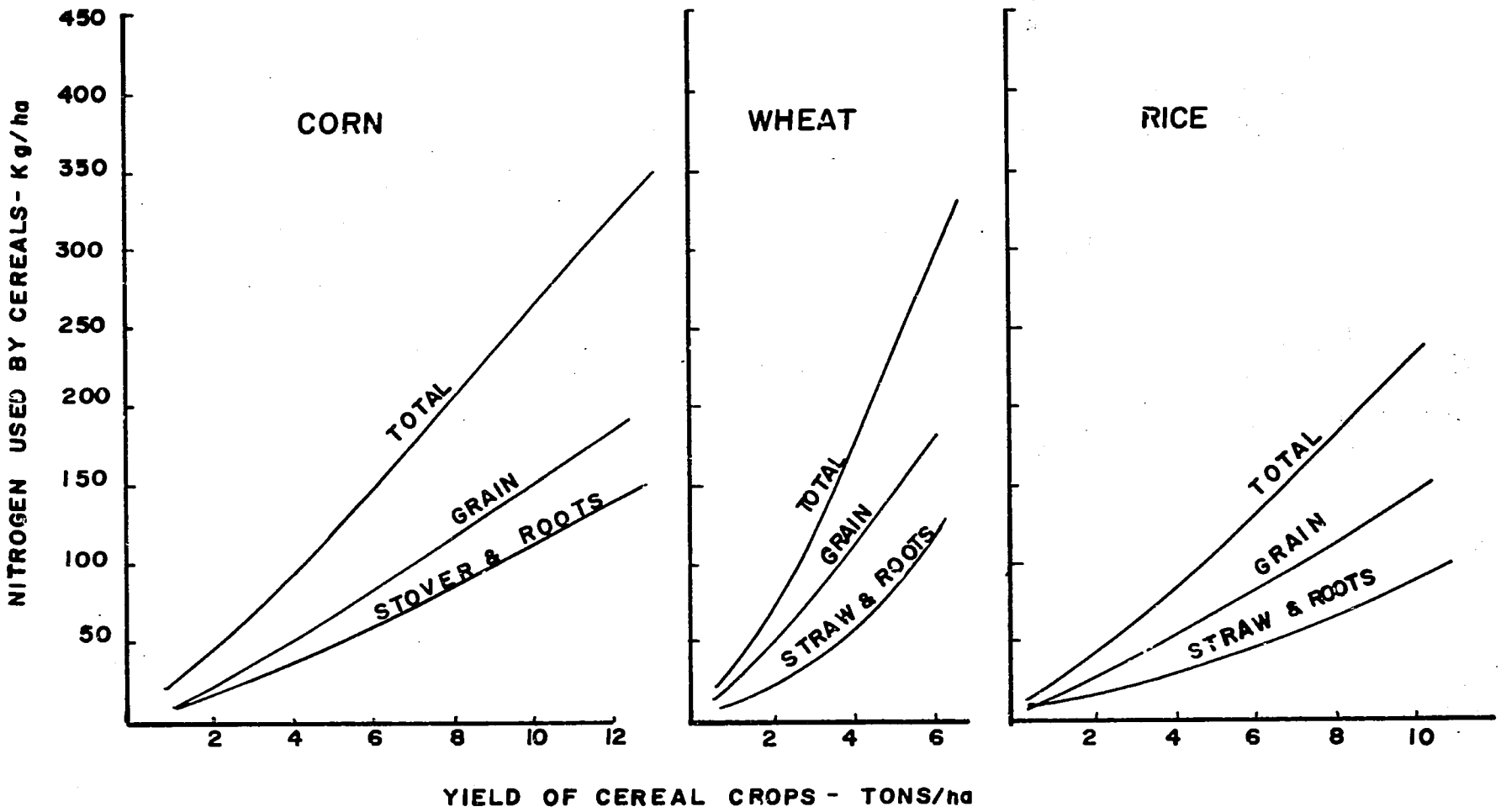

Figure 3. A comparison of nitrogen use by corn, wheat, and rice at a range of yield level.

How Much Potentially Available Nitrogen is Needed to Produce a Crop?

The efficiency of crop use of potentially available nitrogen can be realistically evaluated only from field plot experience. Test and guide procedures have been devised and employed to reflect crop needs for nitrogen and efficiency of plant use, but knowledge of field performance is always the crucial measure.

An appraisal of nitrogen needs for the production of corn, wheat, and rice has been made using field response data (Figures 4, 5, and 6). The nitrogen response information was obtained by a survey of a large body of field plot data. (See literature section for specific crops). In each instance, two factors were noted. They were: 1) the calculated quantity of fertilizer nitrogen needed to achieve a one-ton increase in yield; and 2) the check yield from which the increment increase was measured. Most of the data represented yields where a first increment of fertilizer nitrogen was applied. However, an important segment of the data represent second and third increment additions of fertilizer. Also each observation which was used was one that was clearly in the response range in that the next higher increment addition of nitrogen produced some additional increase in yield.

The data for corn came from an evaluation of 111 field sites and the use of 212 response observations. For nitrogen response in wheat, data from 24 field sites were reviewed and 44 response observations were tabulated. The rice data represent 70 field sites and 103 response observations.

The data summarized covered a wide range of responses to nitrogen, as well as a wide range of initial yield levels. In the cases for corn and wheat, a trend was noted toward greater nitrogen needs for increment increases in yield at high than at low check yields. However, in both instances the regression constants

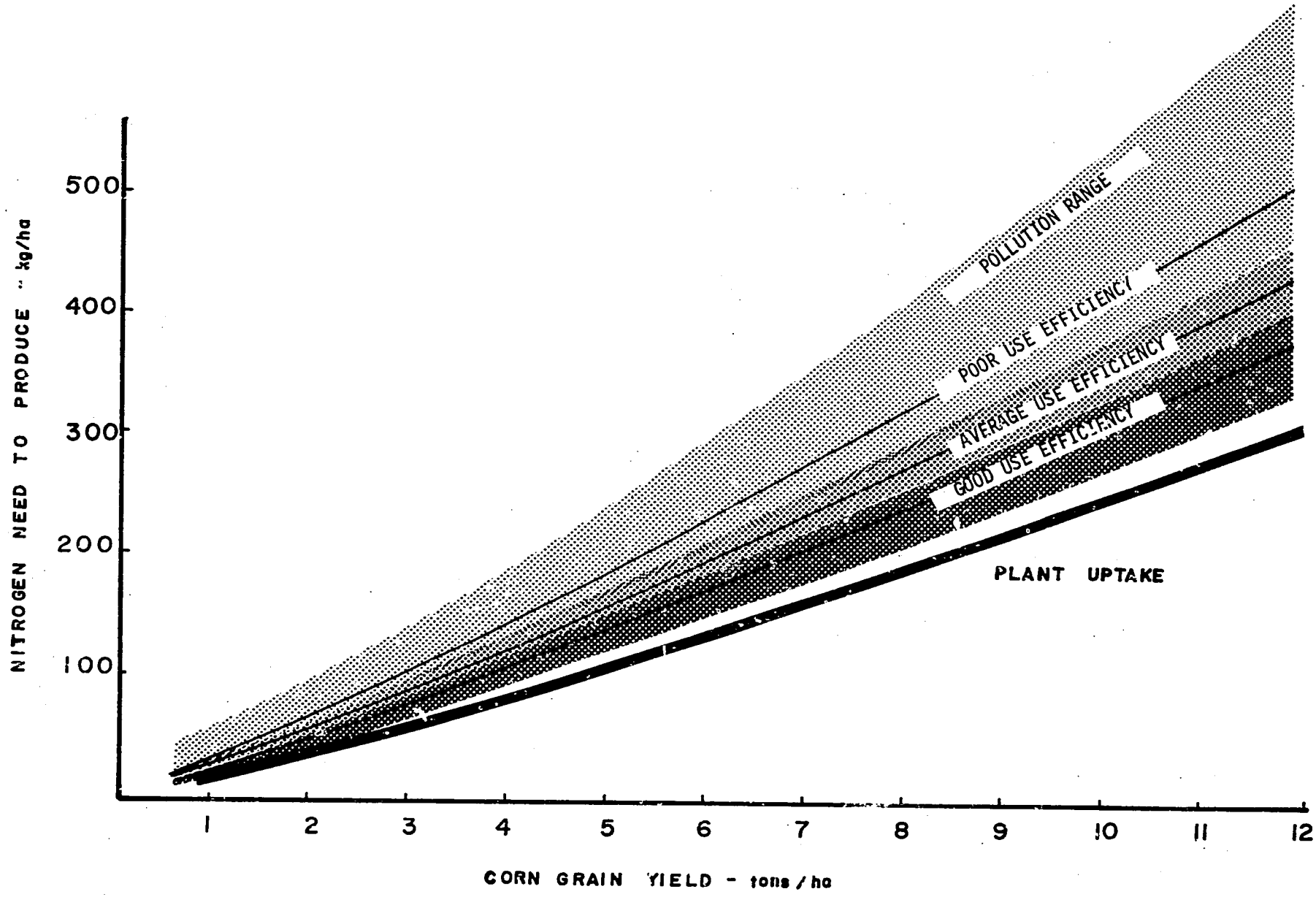

Figure 4. Nitrogen use by corn along with appraisals of need for available nitrogen.

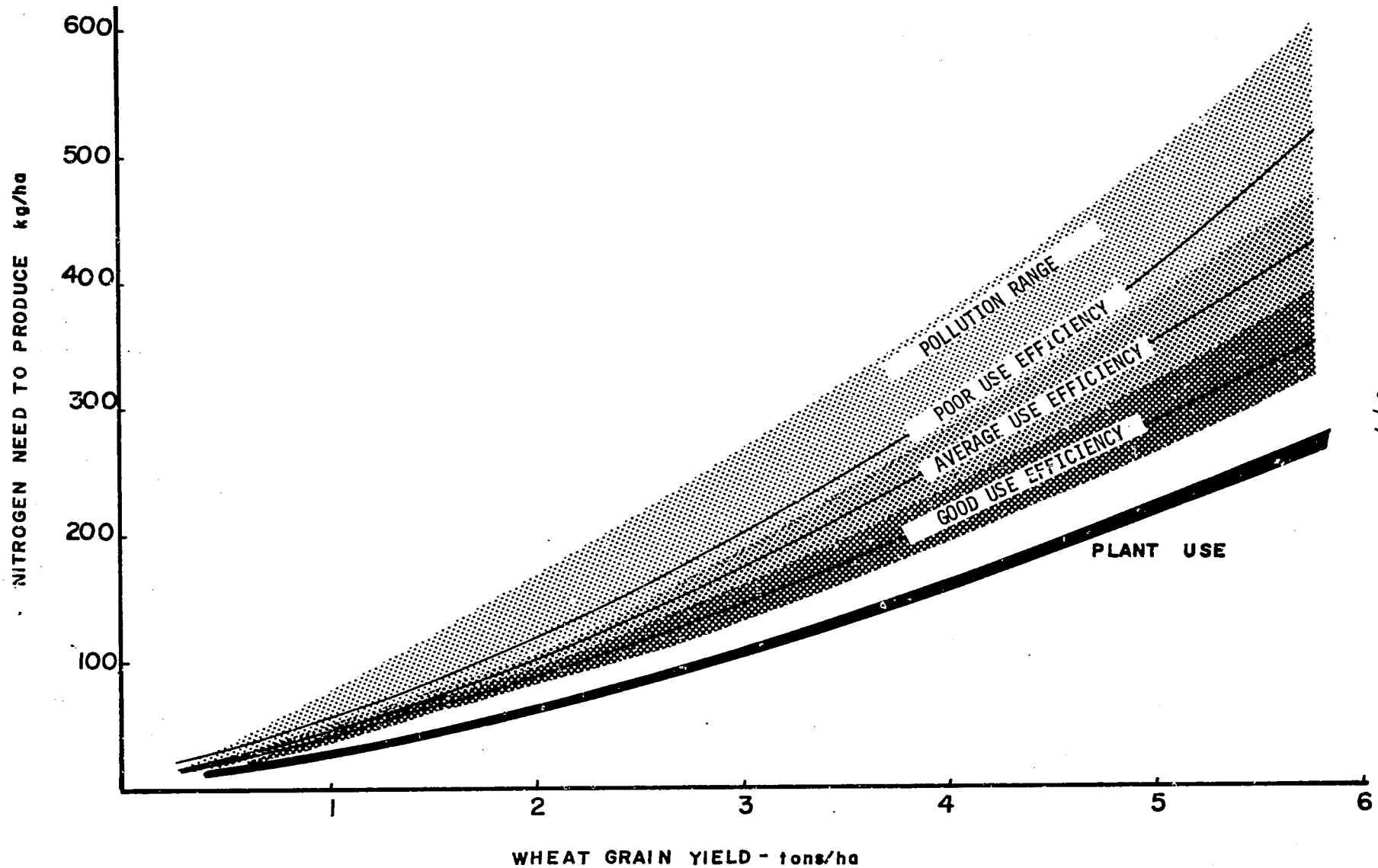

Figure 5. Nitrogen use by wheat along with appraisals of need for available nitrogen.

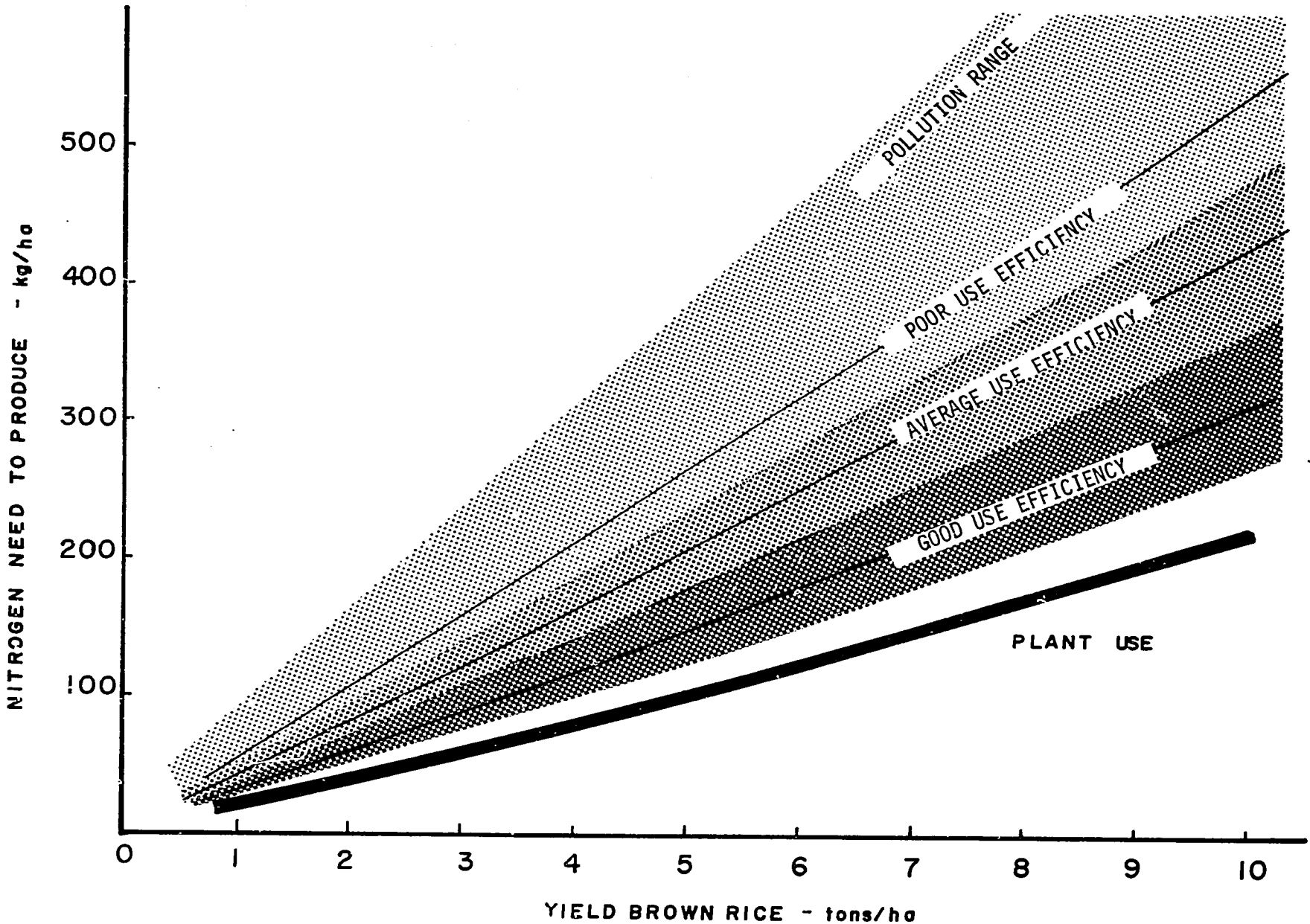

Figure 6. Nitrogen use by rice along with appraisals of need for available nitrogen.

were not significant. For corn the regression equation was:

$$N = 30 + 1.3\ I$$

in which

N = kg nitrogen to obtain a one-ton increase in corn yield and

I = the check yield in tons/ha from which the increment increase was measured

For the wheat data the regression equation was:

$$N = 58.1 + 0.005\ I$$

Owing to the large variations in rice yield response to nitrogen no regression equations were calculated. The mean response was 43 kg nitrogen per ton increase in brown rice.

In all instances the premise was followed that somewhat larger increments of nitrogen were required for unit increases in yield at high than at low yield levels. This results in nitrogen requirement curves which are slightly curvilinear. These nitrogen requirement trends are in keeping with response observations and also with crop use data. However, in field situations the limited yield range covered in single experiments is usually too small to accurably measure the deviations from linearity. A wide range of yield situations is necessary to observe the spectrum of differences at high and low yield levels.

Use Efficiency - A Case for Dual Function Response Models

The summarizations of the response data and the proposed methods of use of the summaries are based on the premise that nitrogen fertilizer response functions are essentially rectilinear. Nitrogen use by cereals closely approaches a linear function of grain yield. Nitrogen needs for production, likewise, are linearly related to crop use at all yield levels. An examination of a large body of nitrogen response data for corn shows that rectilinear or combinations of linear functions describe the data from most individual sites better than curvilinear models. This is for an examination of single site, single season studies. The models in these instances would have three elements. They are a base intercept value reflecting the yield without nitrogen, a linear slope segment which evaluates the efficiency of nitrogen use, and a horizonal vertex segment representing the maximum productivity at the site.

Perhaps the trend among agronomists to employ continuous curvilinear models stems in large part from the practice of combining for analyses a large number of site studies from a single year or to combine studies from several seasons. In combined data, continuous curvilinear functions generally fit the average responses better than linear functions even though the data from each individual site may be best evaluated by a rectilinear model.

In combining data from different sites and from different seasons, unlike elements are associated. Parts of the plateau zone from one site may become associated with a zone of response from another. In using rates of fertilization as the independent variable, the vertex in one response function becomes associated with the initial response zone of another. Sites and seasons permitting high production are averaged in with sites and seasons of low productivity and fertilizer use efficiency. If data are to be combined for analyses, systems should be devised to combine

similar segments of the response functions. In many instances the use of curvilinear models for describing data was induced by creating artifacts through the process of making arithmetical means. The simple exercise of averaging a series of diverse rectilinear sets of nitrogen fertilizer response data will serve to illustrate this fact.

Rectilinear functions can be effectively employed to describe many if not most fertilizer response data from single site, single season experiments. Even so, it cannot be assumed that the response functions are strictly linear. The data examined in this study with reference to nitrogen indicate that somewhat higher amounts of fertilizer are required to increase yields by unit increments at high than at low yield levels. The response functions, therefore, deviate somewhat from linearity. Nevertheless, the total response situation at any site or season can be closely described by two separate functions. The horizonal function for practical prediction purposes can be considered a straight line and to be parallel to the fertilizer rate axis. The response function should be slightly convex downward when fertilizer increments are plotted on the horizonal axis. The point of intersection of the two functions represents the biological optimum (the lowest rate of fertilizer addition needed to attain near maximum yield).

V. NATURAL NITROGEN SUPPLY PROCESSES --THEIR CHARACTERISTICS AND LIMITATIONS

The natural supply processes include: 1) mineralization of nitrogen from soil organic matter and from crop residues and the reverse process of immobilization in the decomposition of plant and animal debris and soil organic matter; 2) fixation of nitrogen from the atmosphere largely through biological processes; 3) nitrogen added through rain and other forms of precipitation; and 4) some release of nitrogen through weathering of soil primary minerals. Until the advent of chemical fertilizer, agriculture was dependent upon the natural supply processes for crop production. Soil management practices in the early agricultural eras were designed to maximize the use of these processes in providing nitrogen for crop production. Research, also, was heavily oriented toward understanding the processes and in improving them as vehicles to provide nitrogen in agriculture. In the modern agricultural setting these natural processes need to be re-examined as sources of nitrogen in crop production. They have a number of peculiarities which limit their capacities to provide adequate nitrogen in this age of technology (Bartholomew, 1971).

Soil Organic Matter

The nitrogen in soil organic matter has been and is yet an important source of supply of nitrogen for crop production. However, soil nitrogen is not inexhaustible and it must decline in quantity in the soil in order to supply net amounts of nitrogen to crops grown on the land. Consideration of several factors associated with formation and decomposition of soil organic nitrogen will serve to illustrate its importance and also its limitations as a source of nitrogen in crop production.

Nitrogen in the soil is largely in organic form and is an integral part of the soil organic matter system. Changes in organic matter are always accompanied by similar changes in organic nitrogen.

Organic matter is a temporary product -- a stage in a natural cycle of elements. Each increment of organic matter originated as a particle of plant or animal residue, and it remains in the soil while it passes through the several slow biological changes that eventually convert it to carbon dioxide, water, ammonium, and other mineral elements.

The soil supply of organic matter is replenished by periodic additions of fresh plant or animal residues. Organic nitrogen additions and biological decomposition proceed simultaneously and almost continuously in soils. Under any sustained system of crop and soil management, these two processes tend to approach each other in magnitude such that mineralization balances immobilization (Bartholomew and Kirkham, 1960). When this condition is attained that system is considered in equilibrium.

Soil areas may differ quite markedly in the equilibrium level of soil nitrogen attained after long periods of constant soil management. This is best illustrated by reference to the general mathematical expression used to describe soil nitrogen changes with time (Woodruff, 1949):

$$[dN/dT = A - r N] \qquad [1]$$

is the primary differential equation which states that the rate of change in soil nitrogen is positively related to the rate of addition and inversely related to the rate of decomposition. $\underline{N}$ in the equation is the soil nitrogen content. $\underline{A}$ is constant and is the annual rate of addition. The rate of decomposition, r, is a given fraction of the organic nitrogen in the soil and represents

the annual rate of mineralization. Upon integration the expression in equation [2] results:

$$N = \frac{A}{r} - \frac{A\,e^{-rt}}{r} + No\,e^{-rt} \qquad [2]$$

The function e^{-rt} varies from 1 to 0 as rt varies from 0 to some very large number. Therefore, after a long time (t), the last two components in the equation approach zero and the equation [2] becomes:

$$N = A/r \qquad [3]$$

and

$$rN = A \qquad [4]$$

This means (equation [4]) that addition is equal to decomposition. From equation [3] we can see that the amount of nitrogen in the soil at final equilibrium is influenced by both the rate of addition and the rate of decomposition.

The implications and consequences of equilibrium situations in soil organic nitrogen need to be emphasized. At equilibrium additions are essentially balanced by decomposition. The total quantity of nitrogen in the soil remains unchanged. Consequently, the net amount which can and is supplied to a crop is zero. Under these conditions, there must be as much organic nitrogen returned to the soil as is liberated from decomposition. A critical examination of equilibrium conditions revels that when a part of the crop is harvested and removed from the land, equilibrium conditions in organic matter can exist only if the nitrogen and organic matter inputs are supplemented from sources apart from the land area in question. Fallow areas and permanent pastures most nearly provide situations where equilibrium situations could exist without substantial fertility input from outside sources. Also, at very low levels of soil nitrogen, the additions from

rainwater and from nonsymbiotic nitrogen fixation may furnish enough nitrogen from outside sources to permit low levels of crop removal for long and sustained minimum production.

During periods of virgin or noncultivated conditions, certain soils tended to build up in soil organic matter and soil nitrogen. Some arable soils accumulated more than 10,000 kg of nitrogen per hectare under virgin conditions (Schreiner and Brown, 1938). Upon the advent of cultivation this equilibrium was disturbed. Either the rate of addition of soil organic nitrogen or the rate of decomposition or both were altered, such that a new equilibrium level was approached. In most instances this new level of organic matter was lower than that occurring under virgin conditions. During the first few years of cultivation of such soils, there may have been mineralized annually as much as 200-400 kg/ha of available nitrogen for possible crop use. As cultivation continued and the organic nitrogen declined, the quantity of nitrogen becoming available each year declined. After long periods of cultivation the soil organic matter became depleted as a major source of available nitrogen, and unless legumes were grown the annual available nitrogen from natural supply processes became chiefly that from rainwater and from nonsymbiotic nitrogen fixation.

Soil organic matter must be declining in quantity in order to supply net amounts of nitrogen for crops grown on the soil. This is still happening in some areas of the world. There is no simple method for determining the extent to which soil areas have attained organic matter and organic nitrogen equilibrium. Soil test procedures largely reflect total mineralization or total organic nitrogen. The time period which the soil has been under constant cultivation is the best guide. In view of the experience with some long time soil and crop management experiments in temperate regions, a new equilibrium in nitrogen and soil organic matter is closely approached in 60 to 100 years of constant management

(Bartholomew and Kirkham, 1960). In some tropical and semitropical areas the time to attain organic matter and nitrogen equilibrium may be much shorter.

Organic nitrogen contents at equilibrium vary because of both soil properties and management practices. Volcanic ash soils in particular tend to hold and stabilize organic matter. The factors responsible for this apparent stabilization and the conditions which induce mineralization warrant research attention.

Management systems which produce and return to the soil large annual additions of crop residues result in higher equilibrium levels of organic matter than do low yields and low additions of residues.

Fallow systems where the land areas are taken out of cultivation for periods of so called "rest" and/or "rejuvenation" have their influences on subsequent crop production largely from factors other than soil organic nitrogen. Clean fallow in areas of limited rainfall permits the accumulation of water and an increase in available nitrogen. These accumulations generally permit the subsequent growth of a good crop.

Bush fallow or shifting cultivation allows for the accumulation of plant nutrient supplies in a vegetation cover and the associated litter on the soil surface (Bartholomew et al., 1953; Nye and Greenland, 1960). When the land is reclaimed the vegetation cover is usually cut and burned. The mineral elements are released by burning and with the exception of nitrogen and some sulfur are deposited as ash on the surface of the land. Crops which follow this reclamation benefit from the accumulations and deposition of plant nutrients on the soil in available form.

Some small increases in available nitrogen supply occur as a result of bush fallow irrespective of the loss of nitrogen by burning. This increase in available nitrogen apparently results from the litter accumulation, from roots, and from the probable

effect of the heat of burning on the biological release of nitrogen. The stimulation in the rate of release of available nitrogen is normally of short duration. Most generally the fertility supplying effects of shifting cultivation are evident for only two to four cropping seasons. The fertility influences imparted by accumulations of soil organic matter and soil organic nitrogen tend to be of much longer duration.

The important aspects in the nitrogen equilibrium phenomenon in soil are the rates of addition of organic matter to the soil and the rates of decomposition. In temperate regions the cold season inhibits both production and decomposition of organic matter and nitrogen. A prolonged dry season in semitropical zones may have much the same kind of influence on the soil organic nitrogen supply as a cold winter season in the temperate regions.

Many of the major crop land areas of the world have now been cultivated for extended periods of time. The organic matter contents have closely approached equilibrium with current soil management. Where the use of nitrogen fertilizers has been small or nil, the yields of major crops largely reflect the magnitudes of the natural nitrogen supply processes from rain water and nonsymbiotic nitrogen fixation. Where the use of nitrogen fertilizers has been small or nil, the yields of corn and wheat have been in the range of 600 to 1200 and 400 to 800 kg/ha respectively. Such yield levels do not result in the removal of more than 7-16 kg/ha of nitrogen in the grain products. The nitrogen required for these levels of production is close to that expected from nonsymbiotic fixation and from rain.

There are yet large areas of land in tropical regions that have not been cleared and cultivated within the known history of the land. The clearing and cultivation of some of such areas is anticipated in the future. The inland regions of Brazil are examples. Following clearing and cultivation the soil would be

expected to furnish some substantial amounts of nitrogen. The amounts furnished, the rate of anticipated decline in soil nitrogen, and the time required for achieving equilibrium are important research topics.

Nitrogen Fixation by Biological Agents

Biological nitrogen fixation processes have been largely responsible for providing the large quantities of nitrogen which are currently used by and tied up in plants and animals and in the decomposed residues found in soil (soil organic matter). Moreover, biological fixation processes still supply the major part of the nitrogen for crop production in world agriculture.

The chief process is symbiotic nitrogen fixation in which a host plant (mainly leguminosae) and bacteria function in symbiosis. Numerous host plants function is this way. A large number are domestic in that they are employed in crop husbandry. Symbiotic process of nitrogen fixation may supply a part or all of the nitrogen used by the host plant. As a result of this process, other crop plants which are associated with or which follow the host in a crop sequence may benefit by being supplied increased nitrogen. An understanding of some aspects of the fixation process provides a basis for determining what may be expected of the host plant and the benefit which may accrue to the associated crops.

The amounts of nitrogen fixed per acre per year under field conditions have been estimated by several investigators. It is presumed that in most instances the estimates are based largely on the quantities of total nitrogen taken up and immobilized in the plant tissue. This may or may not evaluate fixation. Legumes and other host plants generally are as efficient users of available inorganic nitrogen as nonlegumes. Total nitrogen contained in leguminous crops range from a few kg/ha in poor stands of legumes

to as much as 300 to 500 kg/ha in large yields of soybeans (Anonymous, 1971), and several cuttings of alfalfa (Table 2).

Fixation is Growth Related

An important aspect of biological nitrogen fixation is that the processes are growth related (Allos and Bartholomew, 1959). In both symbiotic and nonsymbiotic fixation, nitrogen is fixed and used only as it is needed for growth of the bacteria and/or the host plant. The fixation process does not result in indiscriminate nitrogen fixation in which an excess of fixed nitrogen gets transported to the exterior of the bacterial cell in the case of nonsymbiotic fixation or to the outside of the host plant in the case of symbiotic fixation. Fixation is growth bound and the fixation processes are in some way regulated by growth processes and by needs for nitrogen.

The total quantity of nitrogen fixed by the symbiotic process is closely related to the total amount of growth made by the host plant (Allos, 1956). For example; a host crop which makes a large total growth and has a high nitrogen content would result in considerably more nitrogen fixation from the atmosphere than a host plant under the same circumstances which makes only a small total growth.

Mineral Nitrogen Substitutes for Fixation

Another important factor to consider is that in both symbiotic and nonsymbiotic processes fixation is inhibited by the presence of available inorganic nitrogen (Allos and Bartholomew, 1959; Jensen, 1950). When mineral nitrogen is in the system and available for use by the bacteria and/or the host plant, the inorganic nitrogen is absorbed and used first with the fixation processes functioning only to supply the nitrogen deficit. In other words, available nitrogen substitutes for and replaces that of the fixation

Table 2. Yield and nitrogen content of some legumes

Legume crop and plant parts	Dry matter		Nitrogen	
	Tops	Roots	Tops	Roots
	lbs/A		lbs/A	
Sweet clover - fall of seeding year 1/	8860	1210	136	15
Sweet clover - maturity in 2nd year 1/	9710	620	138	7
Soybeans - straw + beans (19.3 bu/A) 2/	5540		88	
Soybeans - straw + beans (22.1 bu/A) 2/	6281		129	
Soybeans - straw + beans (20.4 bu/A) 3/	5174		179.1	
Soybeans - straw + beans (65.5 bu/A) 3/	10960		345.4	
Alfalfa - fall of seeding year 4/	1695	1270	54	34
Ladino clover - fall of seeding year 4/	2171	435	64	10
Vetch - winter clover - tops and roots 5/	2655		107	
Austria winter peas -winter cover-tops & roots 5/	1780		68	
Crimsen clover -winter cover- tops and roots 1/	3159		101	

1/ Willard. 1927.
2/ Norman. 1944.
3/ Weber. 1966.
4/ Fribourg and Johnson. 1955.
5/ North Carolina Agron. Res. Rept. No. 12. 1954.

processes. A very small but sustained concentration of mineral nitrogen in the soil solution will largely inhibit fixation.

Fixation may be inhibited without inhibiting nodulation. The presence of nodules on host plants does not necessarily indicate that extensive fixation is or has taken place (Allos, 1956). When small but sustained amounts of available nitrogen are supplied to leguminous plants, the normal infection processes of the roots may take place and nodules be formed but very little if any nitrogen fixed. With higher concentrations of available nitrogen even the formation of nodules is prevented.

Leguminous and other plants which enter into symbiotic nitrogen fixing associations may often fix only a part of the nitrogen contained in their tissue when grown on normal agricultural soils (Allos, 1956). The higher the general level of nitrogen fertility in the soil the smaller the proportion of nitrogen fixed. The greatest fixation takes place in soil situations which have low available nitrogen but otherwise high fertility and productivity.

Responses of Legumes to Nitrogen Fertilization

Legumes may respond in growth and yield to the presence of a favorable quantity of mineral soil nitrogen (Thornton, 1948). Greenhouse tests have demonstrated such responses (Allos and Bartholomew, 1959). Moreover, maximum yields of soybeans have often been produced where high quantities of nitrogen fertilizers have been applied (Anonymous, 1969a, 1969b, 1969c; Pahl, 1970).

Nitrogen fertilizer management for the production of legumes is largely an unknown field. About all that has been done so far is to try application practices which have been successful for nonleguminous crops. Some serious studies should be undertaken on nitrogen fertilization of legumes in the tropics, especially those which are important food crops.

Influence of Legumes on Associated Crops

The influence of legumes on associated crops or on crops which follow the legume is difficult to assess. During the active growing period of leguminous plants, very little nitrogen escapes and becomes available to associated crops (Chan, 1970; Moncada, 1965) (Figure 7). It is only when the legume becomes mature or when environmental conditions induce parts of the plant to die that the nitrogen in the legume tissue begins to become available through microbial decomposition. Perennial legumes begin to exert a major influence on associated plants after the season of establishment and annual legumes at maturity or shortly thereafter when decomposition of tops and root occurs.

The nitrogen supplied to crops following meadow and catch crops has been evaluated by Shrader et al. (1966). The crop immediately following the legume obtained a rather large quantity of available nitrogen from the preceeding legume. Their data indicate that a crop which followed a good legume crop in the rotation benefited to the extent of 110 to 130 kg of nitrogen per hectare. The benefit to the second crop following the legume was 1/3 to 1/2 of that obtained in the first crop.

The increase in soil available nitrogen immediately following the growth of the legume arises in large part from the decomposition of residues returned to the soil. The increased available nitrogen following legume culture may also reflect some buildup of total nitrogen in the soil where meadow occurs frequently.

Green manure and cover crops vary markedly in the quantities of nitrogen which they supply to a crop which follows. All of the nitrogen contained in the green manure is not available to the following crop. The proportion of the nitrogen in the legume crop which becomes available is closely related to the percentage nitrogen in the residue returned to the soil (Bartholomew, 1965). In general, green manure crops have resulted in growth responses in crops

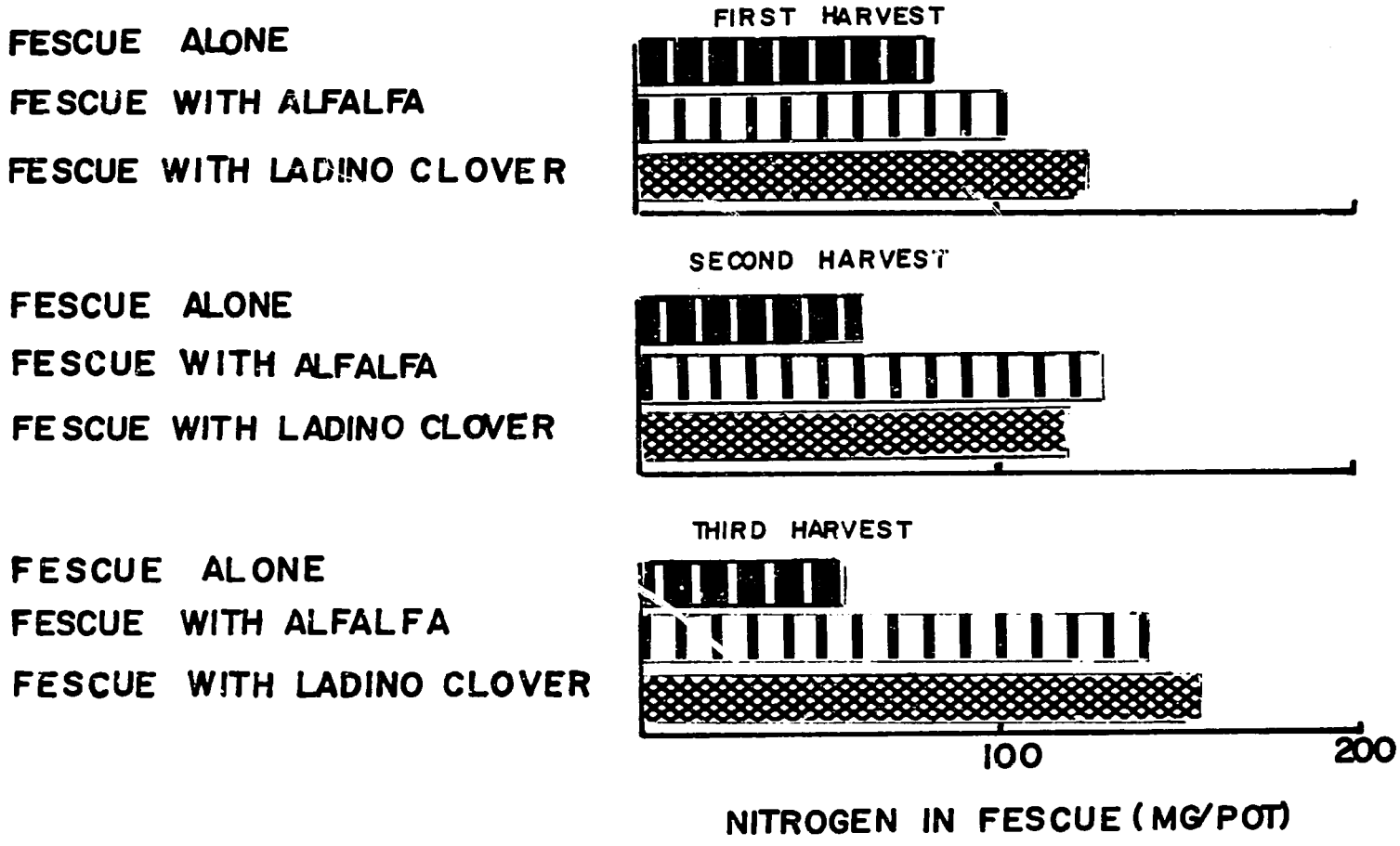

Figure 7. The influence of legumes in supplying nitrogen to associated grasses during the establishment phases of growth.(From Moncada, 1965).

which followed equivalent to those obtained from the addition of from 10 to 60 kg of nitrogen per hectare. The nitrogen supplied is not large in terms of fertilizer equivalents. The economics of the practice need to be critically considered before recommending green manures as a source of nitrogen to crops which follow.

Fixation by Free Living Microorganisms

In nonsymbiotic nitrogen fixation by free living bacteria in the soil a limiting condition is food energy for the growth of the organism (Moore, 1966). For example, 10 mg of nitrogen fixed per gram of organic food decomposed is near the maximum efficiency obtained by young, fast growing, heterotrophic nitrogen fixing bacteria (Azotobacter). This means that for 10 kg of nitrogen fixed per hectare the nitrogen fixing bacteria would have to have consumed 1000 kg of energy food. In the case of nitrogen fixing algae the energy would come from light (Mayland *et al.*, 1966; Singh, 1961; Watanabe, 1966). This rate of fixation further assumes maximum efficiency in the use of food energy and the absence of available nitrogen. These two conditions seldom occur in a soil system. The evidence strongly suggests very little nonsymbiotic nitrogen fixation in most soils (Jensen, 1950).

In Brazil, a favorable environment for nonsymbiotic nitrogen fixation is under study (Döbereiner, 1961, 1969). *Azotobacter paspali* has been noted to thrive in the root zones of sugarcane and some species of paspalum. The plants, through the root system, may provide sufficient energy to support significant fixation. A pseudo-symbiotic association appears feasible. Its importance to agriculture warrants further study. However, if the known principles influencing nitrogen fixation apply to the above associations, only fair to moderate yields of the particular crops could be expected from nitrogen fixation and the higher yields often required for modern economic agriculture would necessitate the addition of nitrogen fertilizer.

Nitrogen in Precipitation and Dust Particles

Rain and other forms of precipitation carry varying quantities of nitrogen. The amounts produced from these sources have been measured at numerous locations throughout the world (see literature reviewed). Most of the studies dealt with ammonium and nitrate ions. The reported quantities have ranged from 1 to in excess of 50 kg/ha/year. The mean of the several estimates would be in the order of magnitude of 7-9 kg/ha/year. The largest quantities have been noted in West Africa (Jones and Bromfield, 1970; Thornton, 1965; Gore, 1968).

In addition to the inorganic nitrogen coming to the soil through precipitation sources, nitrogen also comes into soil areas as dust, part of which may be in organic form. The latter contribution has been less well surveyed but can be appreciable in some areas. The average total nitrogen coming from both rain and dust may range 7-11 kg/ha/year.

The nitrogen coming into the soils through precipitation or by way of air transported particulate matter cannot be considered as net gains. Part of the airborne nitrogen originated in soil and was merely translocated from one site to another. Part, on the other hand, probably came from nonsoil sources. Vesser (1964) lists the following sources of nitrogen in rain water: 1) electrical fixation; 2) photochemical oxidation; 3) meteor trails; 4) dust; 5) industrial contamination (smoke and fumes); 6) oceans and lakes.

In soil areas having low nitrogen contents where little nitrogen could be carried from the soil surface by air currents, precipitation and dust may provide a quantity of available nitrogen equivalent in magnitude to that supplied through decomposition of organic matter.

Crop Residues and Nitrogen Availability

The tie-up (immobilization) and release (mineralization) of nitrogen in association with the decomposition of crop residues has important influences on nitrogen availability in soils used for cropping (Bartholomew, 1965). Some aspects of the processes are discussed below.

First, ordinary crop residues are rather similar in capacity to tie-up nitrogen and will retain from 10 to 14 kg of organic nitrogen per ton of original residue for one or more cropping periods. If the residue originally contains less nitrogen than needed by the microorganisms for decomposition, inorganic nitrogen will be absorbed from the soil and immobilized by the organisms. If the residue contains more than is needed by the microbes, the excess nitrogen will be mineralized and appear as inorganic nitrogen in the soil.

The major tie-up and release processes come early in the decomposition processes. In soil they are essentially complete within the first two to four weeks of decomposition. Low nitrogen residues which immobilize extra soil nitrogen tend to retain the total immobilized nitrogen for two or more seasons without appreciable release. High nitrogen residues tend to release small amounts of nitrogen after the first initial decomposition surge. This results in small but measurable amounts of nitrogen becoming available from the high nitrogen residue during the second and subsequent seasons of decomposition. After the first early surges in decomposition crop residues continue to decay slowly with the loss of carbon dioxide and water. They tend to retain the nitrogen. Consequently, the percentage nitrogen increases in the residue material and the C:N ratio decreases.

Environmental factors, chiefly weather, influence the nitrogen tie-up and release processes chiefly by influencing the rate of decomposition of the crop residues. Such environmental factors do

not significantly alter the amount of nitrogen retained or released by residues at particular stages of decomposition.

Many observed cropping and soil management practices exert part or all of their influence upon the soil or the crop through modification or control of the tie-up and release of nitrogen. The marked influence of a crop upon one which follows is quite often largely due to the influence of the crop residue on the nitrogen supply from the soil.

The amounts and kinds of residues left on the land and the manner in which the residues are managed determine the rate and extent of nitrogen tie-up and/or release. The practical handling of the crop residues, including plowing and subsurface tillage and the time of the year when tillage operations are carried out, may alter the nitrogen supply. Residues left on the surface decompose more slowly than those plowed under. This slow decomposition, along with the fact that the surface residues are in contact with less soil material, results in a much slower tie-up of nitrogen in the case of low nitrogen residues and a slower release of nitrogen from high nitrogen residues than would be found when residues are incorporated into the soil by tillage. Surface mulches also modify soil temperature and moisture content which in turn influence tie-up and release of nitrogen in crop residues and soil organic matter.

Fall plowing and plowing under low nitrogen residues well in advance of planting a crop usually result in more soil nitrogen being available to the next crop than plowing just prior to planting. The chief reasons are: first, weeds and other plants are killed which absorb soil nitrogen, leaving available nitrogen to accumulate in the soil; and second, the nitrogen tie-up processes of decomposition will have been satisfied long before planting. Consequently the nitrogen mineralized from the soil will be available to the crop and not re-absorbed by the residue during early stages of decomposition. Plowing under leguminous residues too far in advance

of planting a subsequent crop may provide opportunity for nitrogen loss by denitrification or by leaching.

Cultivation of the soil has been reported to stimulate microbial activity and result in increased nitrogen becoming available from the soil. The validity of this principle has never been adequately investigated. It may or may not be correct. Factors other than just disturbing and aerating the soil, in most instances, can explain most of the benefits of cultivation. Changes in soil temperature or in soil moisture which are brought about by cultivation will generally account for the effects of cultivation.

The carry-over effect of nitrogen fertilization into the second season following application may result in part from the amount and composition of the crop residues which are left on and in the soil, and in part from inorganic nitrogen remaining in the root zone. Generally, larger amounts of residue from nonlegumes are returned to the soil from the application of high rates than from low rates of nitrogen fertilizer. However, the higher nitrogen contents of the residues induced by high nitrogen fertilization would tend to more than offset the effect of the amount of residue in total nitrogen immobilization. For example; 1,500 kg of corn residue containing 0.6 percent nitrogen may tie-up more nitrogen than 2,500 kg of residue containing 0.8 percent nitrogen.

VI. PROCESSES CONTROLLING CROP USE OF NITROGEN

Role of Water on Nitrogen Uptake by Roots

The extent to which plant roots absorb soluble soil nitrogen is largely dependent upon soil water. Water is directly involved in the transport of nitrogen from soil to the root boundaries. Water serves to move available nitrogen within and from the root zones.

In plant absorption of nitrogen from soil two steps are involved (Barber, 1962; Barber et al., 1963). The first is the movement of nitrogen from the soil to the root boundaries. The second is the entry of the nitrogen into the plant. In field soil situations the principal rate limiting factor in plant use of nitrogen is transport to the root boundary (Barber and Olsen, 1968).

Transpiration streams carry soluble nitrogen from soil to the root surfaces as plants absorb and transpire water. Soil water films are the media for nitrogen to move to the roots by diffusion. At soil moisture contents favorable for plant absorption of water, nitrogen moves readily to the root surfaces by both mass flow and by diffusion. However, estimates for corn (Barber and Olsen, 1968) indicate that mass flow is the dominant process. At low or unfavorable moisture contents both mass flow and diffusion are largely stopped (Olsen and Kemper, 1968; Liao, 1971); mass flow because water movement in the liquid state is nil and diffusion because both the water cross section for movement and the specific rate of diffusion are reduced at high moisture tensions.

In solution culture nitrate nitrogen can be absorbed relatively more rapidly than water (Minotti, et al., 1968). This indicates active processes in absorption. In soil systems the chief rate limiting process is transport of the nitrogen to the root surface. When moisture conditions are unfavorable the transport processes

are essentially stopped and nitrogen absorption is likewise curtailed (Liao, 1971).

A well known feature of soil water is that all of it is not available to plants. Of the water held at field capacity only from 50 to 60 percent is available to crop plants. Water held at moisture tensions above the wilting point can contain nitrate but would not function in transporting it to crop roots. If nitrate nitrogen absorption by the crop plant is dependent upon water to transport it to the roots, then in some soil systems not more than 50 to 60 percent of the nitrogen could be absorbed by the crop. To effect a large percentage of absorption of the soluble soil nitrate, the water would have to be replenished and recharged a number of times.

Nitrogen Movement and Leaching[2/]

Movement and loss processes under many circumstances are important in regulating available soil nitrogen supplies. The vertical displacement of nitrogen by water in the root zones of crops culminating eventually in leaching into the ground and drainage water probably accounts for the largest quantity of nitrogen lost (Bartholomew, 1964). The extent and severity of vertical movement and of leaching depends entirely on the water infiltration and transpiration regimes in a particular soil region (Terry and McCants, 1970). Since a net downward movement of water is the rule in all arable soils, nitrogen not absorbed by a crop eventually is moved from the solum into ground and drainage water (Bolton, 1968; Low and Armitage, 1970). In some cropping and climatic areas nitrogen losses by leaching frequently occur during

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2/ The term leaching is used here to denote transport down through and out of the root zone.

the growth of crops. Such losses may be seriously increased by irrigation and by prolonged rainfall. In other areas the removal by leaching may occur chiefly during a winter or noncropping season (Wetselaar, 1960; 1962). In yet other areas leaching may be related to seasonal rainfall patterns. In some arid areas leaching may be nil or occur only in seasons of abnormally high precipitation.

Normal precipitation results in water entering the top soil layers. Net movement of water downward through the top few centimeters of soil may be quite extensive. As a result of water absorption by plant roots and subsequent transpiration through the leaves into the atmosphere, the net downward movement of water becomes less in each instance through progressively deeper layers of soil. In plant removal of water from the subsoil, some upward movement of liquid water may occur. When subsoil layers get dry during crop growth, there must be some depth position in the root zone where the net vertical movement of water is zero. Water movement patterns vary markedly among soils, cropping practices, and climatic regions. Also, water movements at single sites may vary considerably among seasons.

In field situations rain may often only wet the surface layer of soil and have little or no influence on the moisture supplies at lower parts of the root zones (Bartholomew, 1971). Where this kind of rainfall pattern predominates, the crop grown would largely obtain its water supply from the top few centimeters of soil. In such situations, nitrate nitrogen could reside in the lower parts of the root zone and be relatively unavailable for plant absorption (Carter et al. , 1967; Herson, et al., 1968).

In other situations high and prolonged rainfall may rapidly remove nitrate nitrogen from the soil horizons from which it could be used by plants. In still other situations where the crop depends upon stored water, nitrogen may be absorbed from particular soil horizons in proportion to the extent of water absorption.

Volatile Losses of Nitrogen

Volatile loss processes may occur by denitrification or by ammonia volatilization. In denitrification the volatile products may be nitrogen oxides or nitrogen gas (Broadbent and Clark, 1965). In ammonia volatilization the product is ammonia. Many evaluations of loss do not distinguish between the processes or the products. Denitrification losses are difficult to evaluate. Direct measurements from arable soils are not yet possible. Indirect measurements provide the only way to estimate the pratical importance of this process. Soil conditions which promote denitrification are: 1) the presence of oxidized forms of nitrogen (nitrate and nitrite); 2) food energy for microbiological activity; and 3) a low partial pressure of oxygen in the soil air.

Losses by ammonia volatilization are variable and are dependent upon the nature of the soil and the kind of ammonia producing fertilizer used (Bartholomew, 1964). In general, ammonia losses occur when ammonia yielding materials are applied to soils in concentrations which exceed the capacities of the affected parts of the soil to adsorb and to hold the ammonia. Sandy or light textured soils have low capacities to retain ammonia and ammonium; so also do plant materials and crop residues.

Some conditions and practices which contribute to ammonia losses are: 1) surface applications of ammonia producing fertilizers to light textured soils; 2) high soil pH; 3) band placement of fertilizer; 4) surface applications of ammonia yielding fertilizer to sods and pastures; and 5) high rates of application of ammoniacal fertilizers.

Total losses by volatile routes are best evaluated by tracer nitrogen in experimental conditions where leaching losses are prevented or are measured. Laboratory, greenhouse, and lysimeter studies provide such conditions. Tracer nitrogen recoveries

from such studies indicate losses from volatile processes of 5 to 15 percent of inorganic fertilizer nitrogen additions in normal arable soils (Bartholomew, 1971). In waterlogged soils the losses may be much higher due to favorable conditions for denitrification.

Total loss processes (volatile plus leaching) have been estimated to involve up to about one-half of the inorganic nitrogen coming into the root zones of arable cropped soils (Allison, 1966; Viets, 1960; Rogers, 1961). In other words, the crops get and use only about half of the otherwise available nitrogen. Such estimates have been made from long time nitrogen balance experiments. Moreover, nitrogen coming from the mineralization of soil organic matter has not been recovered by crops to any greater extent than has nitrogen added to soils as fertilizers (Russell and Voelcker, 1936).

Crop use of nitrogen can and should be more efficient than the 50 percent figure frequently cited. Recoveries of nitrogen by corn and wheat can be generally between 70 and 80 percent when nitrogen is applied in quantities which are needed by the crop, at times in the growing season when it is needed, and in places in the soil such that the crop can use it. The poor use efficiencies noted above are partly the result of application of nitrogen under conditions where it was not needed or when the crop could not absorb and use it.

VII. FORECASTING SOIL AND CROP NEED FOR FERTILIZER NITROGEN

The Bases for Predictions

All systems for assessing nitrogen fertilizer needs make evaluations of some or all of the same set of soil nitrogen regulating factors. These factors as previously stated are: 1) those which supply and regulate the available nitrogen (natural supply processes); 2) those which influence the standard yield or the size of the crop which can be grown (the total need for nitrogen); and 3) those associated with soil site and crop which influence the availability of nitrogen to and uptake of nitrogen by the plant (efficiency of use). The need for fertilizer is to supplement the natural supplies so that adequate nitrogen is provided to obtain the desired crop yield and quality.

The selection of an assessment system depends in part upon which supply, transformation, or use processes appear most important and in part on the crop to be grown, the land area under cultivation, and the biological or economic need for precision in and control of nitrogen applications.

Many soil fertility specialists and agricultural advisors are currently using only crop response experience in making nitrogen fertilizer recommendations (Kurtz and Smith, 1964). Such trends may reflect some degree of negligence toward nitrogen in soil analyses programs as well as a high degree of usefulness of the crop requirement method for assessing the need for nitrogen fertilizers.

Under some circumstances greater precision in making nitrogen fertilizer recommendations can be achieved through the acquisition and use of information to supplement the general experience in an area. This supplemental information can be from soil analyses, from detailed cropping histories of the farm and soil site, from local climatic factors, and from assessments of management

capabilities of the farm operators. The resulting increases in precision of fertilizer use should improve the efficiency of crop production sufficient to more than pay for the extra effort in collecting data.

The value for soil tests for nitrogen or for other supplemental information depends directly on this economic premise. A determination of the value of such procedures is not easy. Decisions for or against their use generally are subjective. Some guidelines and illustrations will be helpful.

General research experience in an area will provide information on the three basic factors (traditional yields, standard yields, and efficiency of use of nitrogen fertilizer). Supplemental information in the form of soil tests helps to refine the estimates of the traditional yields. Other supplemental information on the site or about the operator helps both to estimate the standard yields and the efficiency of nitrogen use. When is such supplemental information useful?

Traditional Yields

In many, if not most, of the cultivated areas of the world, the soils have been farmed for long periods of time and have closely approached equilibrium in soil nitrogen and organic matter. In these soils the net capacity of the soil organic matter to supply nitrogen is very low or nil. In such areas the yields of major crops, where nitrogen fertilizer have not been used, reflects the magnitudes of the natural nitrogen supply processes (Table 3).

Yields of corn in the order of magnitude of 0.5 - 1.0 tons/ha and of wheat from 0.4 - 0.8 tons/ha require supplies of available nitrogen in the range of 15 to 35 kg/ha. Moreover, removals from the land area may not be more than 60 to 70 percent of this amount.

In such areas traditional or check yields would provide a satisfactory evaluation of the natural supply processes and could

Table 3. Corn, wheat, and rice yields from selected countries of the world [1/]

Country	Corn yields - T/ha			Wheat yields -T/ha			Rice yields(paddy) -T/ha		
	1948-52	1963-65	1966-69	1948-52	1963-65	1966-69	1948-52	1963-65	1966-69
Belgium	4.12	4.50	4.53	3.22	3.89	3.78	---	---	---
USSR	1.31	2.28	2.63	0.84	0.91	1.33	1.45	2.57	3.16
British Honduras	0.81	0.61	0.90	---	---	---	2.05	1.02	1.42
Costa Rica	1.32	1.06	1.15	---	---	---	1.42	1.38	2.41
El Salvador	1.05	1.14	1.22	---	---	---	1.69	2.43	2.69
Guatemala	0.65	0.92	0.93	0.58	0.91	0.97	1.18	1.62	2.13
Honduras	0.81	0.82	0.91	0.58	0.56	0.55	1.64	1.64	1.71
Mexico	0.75	1.08	1.14	0.88	2.18	2.56	1.79	2.18	2.56
Nicaragua	1.03	0.85	0.88	---	---	---	1.39	1.33	2.42
Romania	0.81	1.86	2.23	1.02	1.53	1.80	2.23	2.53	2.73
USA	2.49	4.28	4.80	1.12	1.74	1.81	2.56	4.60	4.96
Bolivia	1.39	1.21	1.16	0.61	0.82	0.71	1.52	1.40	1.79
Brazil	1.26	1.28	1.34	0.74	0.71	0.83	1.58	1.57	1.51
Colombia	1.07	0.75	1.05	0.71	0.89	1.17	1.93	1.98	2.38
Ecuador	0.72	0.61	0.58	0.42	0.78	1.00	1.77	1.58	1.64
Paraguay	1.21	1.28	1.13	0.67	0.89	1.07	1.85	2.50	2.34
Peru	1.44	1.50	1.64	0.92	0.97	0.96	3.72	3.96	3.84
Uruguay	0.61	0.58	0.58	0.89	1.08	0.81	3.13	3.08	3.18
Venezuela	0.98	1.07	1.11	0.52	0.55	0.53	1.14	1.84	1.95
India	0.65	1.00	1.03	0.66	0.81	0.94	1.11	1.49	1.49
Turkey	1.25	1.47	1.54	1.00	1.13	1.30	3.51	4.34	4.10
Nigeria	0.89	0.92	1.02	---	---	---	1.46	1.55	1.63
Ruanda	1.01	1.09	1.06	0.79	0.65	0.77	---	---	---
Panama	0.96	0.82	0.80	---	---	---	1.33	1.09	1.17

[1/] From Production Yearbook. Vol. 23, 1969. FAO of the United Nations, Rome.

be used directly in appraisals of nitrogen fertilizer needs.

On the other hand, there are many areas where the traditional yields levels are yet high and variable within a soil region. Recently cleared lands, particularly poorly drained soils, are notable examples. In such areas, traditional yields would be useful only when determined for a specific soil site. Under these circumstances soil tests may find their greatest usefulness.

However, prudence should be used in employing yield data to evaluate nitrogen needs. There are some circumstances where yields are not directly related to nitrogen supply. Also some crops are sensitive to nitrogen and require only small increments of fertilizer nitrogen to supplement the supply from the soil. In these instances, precise measurements of the soil supply may be useful and desirable.

Soil Tests for Nitrogen

Several test procedures have been used to assess availability of soil nitrogen. Some are chemical extraction methods and reflect total soil supply. Some are biological and measure mineralization. All are arbitrary and to be useful must be calibrated with plant use and plant needs.

A review of methods will not be made here. The necessary information on test methods and their probable usefulness can be conveniently found in the literature. The major concern here is an evaluation of the utility of test methods and of alternative ways of getting equally useful information on crop needs for nitrogen.

For convenience of discussion laboratory soil test procedures for nitrogen can be grouped into three categories. They are:

1. Procedures which determine total nitrogen or some chemically extracted fraction of the organic nitrogen. Determination of organic matter would be included in this group.

2. Incubation methods in which a small sample of soil is treated and incubated in the laboratory after which some evaluation is made of total or net mineralization (Fitts, et al., 1955).

3. Measurement of the level of accumulation of inorganic nitrogen in field soils at a particular time or season of the year.

Methods in the first category generally reflect total organic nitrogen. Since availability of nitrogen has been closely related to total soil nitrogen in single soil types and in local climatic zones, the calibration of the test results with crop needs has been useful in guiding nitrogen fertilizer recommendations in some areas.

Some methods in this category have been adapted for use in large scale soil analyses programs. However, they have the inherent shortcomings of not reflecting recent crop residue influence and of being variable among diverse kinds of soils. Rates of mineralization of soil organic matter vary among soil types. Reflections of total nitrogen, therefore, are not accurate measures of available nitrogen unless calibrations are made of each kind of soil.

Methods utilizing rates of mineralization (the second category) more nearly reflect nitrogen availability from soil organic matter than any other analyses systems. They are time consuming to make, however, and like the methods involving total nitrogen they do not reflect the influence of recent additions of crop residue. Like all other methods, the results are arbitrary and must be calibrated with crop growth and the need for fertilizer in order to be useful in soil analyses programs. They can be adapted to fertility analyses service systems.

Measurements of the accumulation of inorganic nitrogen (the third category) at some specified seasons of the year are useful indexes of natural nitrogen supplies in areas of limited rainfall (Giest et al., 1970; Reuss and Giest, 1970). Such methods, where

applicable, tend to reflect nitrogen mineralization rates and also the influence of past cropping management, including the influence of crop residues.

Laboratory soil analyses procedures have been most useful in two kinds of situations. The first is in land areas where the soil organic matter is high and is declining in quantity with the result that a substantial net amount of nitrogen is made available each year from the soil to a crop grown on the land.

The second situation is under limited rainfall conditions and where irrigation is practiced such that inorganic nitrogen accumulates in parts of the root zone and is available for subsequent crop production. Under these circumstances the nitrogen resident in the soil may be high and constitute an important part of that potentially usable by a crop. Also, under these circumstances the quantities of potentially available nitrogen in the soil may vary markedly among sites in local areas.

Laboratory test procedures have had varying degrees of usefulness in soil fertility evaluation programs. Under specified soil and cropping conditions the calibration relationships for some methods have been good. However, no methods have been devised which have been used widely for diverse soil and cropping conditions.

In general the test methods for nitrogen are expensive in terms of analytical time and equipment. This fact suggests the need for a critical appraisal of the usefulness of the nitrogen test methods in soil fertility evaluation programs. Such an appraisal should include consideration of: 1) the type or types of tests which could be used and the unit costs of making the tests; 2) the kind and extent of field calibration research needed to make the test meaningful; 3) kinds and values of the crops to be grown; 4) the general level of nitrogen in the soils and the cropping history of the area; and 5) alternative procedures for getting similar or

equally useful information about nitrogen fertilizer needs and crop responses to fertilizer. For all systems a critical appraisal should be made of the precision in fertilizer recommendations which can be made by the use of a test method and the relationship of this precision to the needs of the crop for nitrogen fertilizer.

Variations in Crop Response to Fertilizer Nitrogen

Under most field situations nitrogen use and need by crops vary from site to site, from season to season, and among systems of management. The extent of these uncontrolled variations determine the degree of precision which is possible and practical in forecasting fertilizer need. Consider some examples.

Data by Colyer and Kroth (1968) show the variations which can occur among seasons at single soil sites (Table 4). The coefficient of variation (C. V.) of the check or no nitrogen plots was 22 percent. The calculated optimum rates of nitrogen have a C. V. of 46 percent.

Baird's (1958) data show the extent of variation among sites of single soil types (Table 5). For Portsmouth soils the check yields ranged from 27-131 bu/a while the yields with ample nitrogen (188 lbs/a) ranged from 45 to 144 bu/a. In soils of the Norfolk series the check yields ranged from 12 to 64 bu/a and the yields with ample nitrogen ranged from 43 to 141 bu/a.

Corn yield data from Laird et al. (1969) show variations among sites in the Puebla Valley, Mexico, in single seasons. The factors reflect production capacities of sites as well as climatic variations (Table 6).

Hunter and Youngen (1955), as well as Pearson et al.(1961), provide data (Tables 7 and 8) which compare sites and seasons.

Table 4. Variations in check (no nitrogen), in calculated economic maximum yields and in fertilizer rates for economic yields. (Data from Colyer and Kroth).

Site	Year	No N	Economic optimum Yield	Fertilizer rate
		kg/ha	kg/ha	kg/ha
Seymour	1961	5090	6697	153.2
	1962	3389	8505	202.1
	1963	5429	-----	------
	1964	4017	7727	133.0
	1965	4431	7990	162.5
	1966	4483	8818	137.8
	1967	3527	-----	------
Marshall	1961	4733	7061	139.4
	1962	5913	6164	21.4
	1963	4525	4387	82.2
	1964	6942	7545	73.6
	1965	6685	9867	142.0
	1966	6555	7658	109.7
	1967	3961	8436	152.9

Table 5. Variations among sites and seasons in corn yields with and without nitrogen. (Data from Baird, 1958 as summarized by Welch, 1960).

1955		1956		1957	
No N*	With N*	No N*	With N*	No N*	With N*
		Norfolk soils (yields in bu/a)			
26	79	47	113	54	82
48	84	42	88	52	138
39	95	42	110	24	90
12	38	31	76	20	101
25	95	23	83	53	91
46	80	55	107	37	60
24	54	57	114	38	79
34	47	29	100	41	63
25	73	64	94	34	65
31	47	32	108	35	40
		41	104	29	33
		28	104	16	27
		51	102	28	26
				33	46
		Portsmouth soils			
70	78	72	88	85	103
45	51	23	39	77	85
64	74	28	40	101	106
59	76	38	114	61	82
42	91	70	90	73	116
100	100	90	90	131	137
53	90	101	99		
26	71	48	99		
56	76				

* No nitrogen values were the mean of treatments 10 and 16. The with nitrogen values were the mean of treatments 8 and 9. All values reported as whole numbers.

Table 6. Variations in corn yield among sites at single seasons. (From Laird *et al.*, 1969).

No N *	With N *	No N *	With N *
T/ha	T/ha	T/ha	T/ha
1964		1965	
0.98	2.82		
2.20	4.15	2.51	4.00
0.85	2.48	2.49	2.31
1.51	1.87	4.46	4.86
2.64	3.94	3.45	4.47
2.47	4.25	1.19	3.32
2.57	2.88	2.38	5.17
0.99	3.61	3.22	5.01
1.39	3.29	1.73	4.37
0.31	4.67	1.37	3.78
1.27	5.11	0.93	4.21
1.56	4.88	0.92	4.10
0.88	4.82	0.89	4.18
1.67	5.07	1.51	3.83
1.37	5.88	1.90	4.63
1.55	4.42	1.29	4.18
0.32	2.23	1.00	3.78
1.79	4.27		
4.55	5.94		

* No N was either treatment 0-0-0 or 0-60-0 whichever had the greater yield. With nitrogen treatment was 120-60-0.

Table 7. Variations in corn yields among farms and among seasons at the same farm. (From Hunter and Youngen, 1955).

Farm	Year	Yields in bu/A	
		No N	Highest with N
Moeller	1950	46.4	112.7
	1951	61.4	112.8
	1952	64.6	147.4
Malheur	1950	131.0	140.8
	1951	85.6	119.0
	1952	112.9	135.5
Hobson	1950	44.4	68.1
Custer	1951	119.0	128.0
V. de W .	1951	109.3	115.8
Cloud	1952	59.2	113.4
Martin	1952	67.6	113.1
Benedict	1952	86.6	110.6

Table 8. Variations among sites and among years at single sites. (From Table 2 Pearson *et al.*, 1961).

Location and year	Yields in bu/A	
	No N	Highest with N
Alabama:		
Bella Mina:		
1955----	65.6	84.3
1957----	49.1	83.9
1959----	25.5	76.1
Prattville:		
1955----	32.3	85.4
1957----	18.5	57.4
1959----	25.0	60.9
Thorsby:		
1956----	61.5	96.5
1958----	49.0	102.0
1959----	38.3	108.9
Mississippi:		
Brooksville:		
1956----	36.1	62.9
1957----	41.9	90.3
1959----	21.8	78.3
Poplarville:		
1956----	33.7	88.5
1957----	21.2	43.8
1958----	13.5	75.0
1959----	6.7	75.4
Georgia:		
Tifton:		
1958----	64.9	112.5
1959----	48.8	85.1
Watkinsville:		
1957----	39.3	102.0
1958----	33.0	107.8
1959----	19.7	138.1

In view of the large site and seasonal variations in both check yields and in standard yields, careful appraisals should be made of the variation patterns. The use of mean values for standard or expected yields is likely to result in less than maximum profits, especially where there is a low probability of occurrence of an adverse climatic season for crop production. The economics of fertilizer use is markedly influenced and complicated by the wide ranges in site and seasonal variations among productivity factors.

How Much Precision is Warranted?

The degree of precision needed and/or attainable in making nitrogen fertilizer recommendations may have considerable influence upon the procedure used to evaluate the level of availability in the soil. Year to year and place to place variations in crop responses to nitrogen fertilizers are large. A well defined optimum rate for one place and time is seldom the optimum for another place and time even for the same type of soil. In view of the rather large seasonal variations in crop response to a specific level of available nitrogen, a high degree of precision in measuring the soil nitrogen may not be useful or warranted in arriving at fertilizer recommendations. A consideration of response data for corn, rice, and wheat suggests that this place to place and season to season variation is well in excess of $\pm$ 15 percent. For purposes of illustration, consider a 15 percent variation in total nitrogen need and its implication on the precision required in fertility evaluation. If moderately high yields are the objective requiring 200 kg per hectare of nitrogen, the variation range would be 170 to 230 kg. If the soil was such that it could furnish somewhere between 50 and 70 kg, anyone of a number of analyses systems may furnish soil available nitrogen evaluations with the necessary degree of precision. Perhaps anyone of the test procedures, where applicable, would be suitable. So also would crop production experience in an area provide sufficiently precise information.

In this respect consider the usefulness of the information in Figure 8. A 1500 kg per hectare crop of corn and 1000 kg crop of wheat on soils where fertility and productivity factors were optimum, but without nitrogen fertilizer, would indicate soil nitrogen availability equal to about 40 kg per hectare. A 3000 kg per hectare crop of corn and 1800 kg per hectare crop of wheat would indicate available nitrogen equivalent to about 90 kg per hectare. These estimates of soil available nitrogen made from crop yield data can be quite precise and the errors are small compared to the errors of estimate in predicting fertilizer nitrogen needs for moderate to high production. In the older cultivated areas where soil nitrogen supplies are relatively low and where productivity factors other than nitrogen are moderate to high, the crop requirement method of assessing nitrogen fertilizer needs would be equally as accurate as employing a soil test procedure and would be much less costly to employ.

In consequence of the large variations in soil site and seasonal needs of crops for nitrogen and the low amounts frequently coming from natural supply processes, soil scientists and agricultural advisors are relying increasingly on general research experiences in areas for information on crop needs for nitrogen and less on soil tests. It should be remembered, however, that any usable information may be helpful and profitable in forecasting nitrogen fertilizer needs. Cropping histories and other local site information are not expensive to acquire. Their use requires expert evaluations but considering their usefulness in relation to cost the procedure is considered profitable. Soil tests, on the other hand, are not so convenient to appraise. For example, to make a soil test may cost the equivalent of 10 kg of nitrogen. On a five hectare tract this cost could be met by a refinement or saving of two or more kg nitrogen per hectare. On one or two hectare tracts a much greater refinement would need be achieved to defray the cost of the

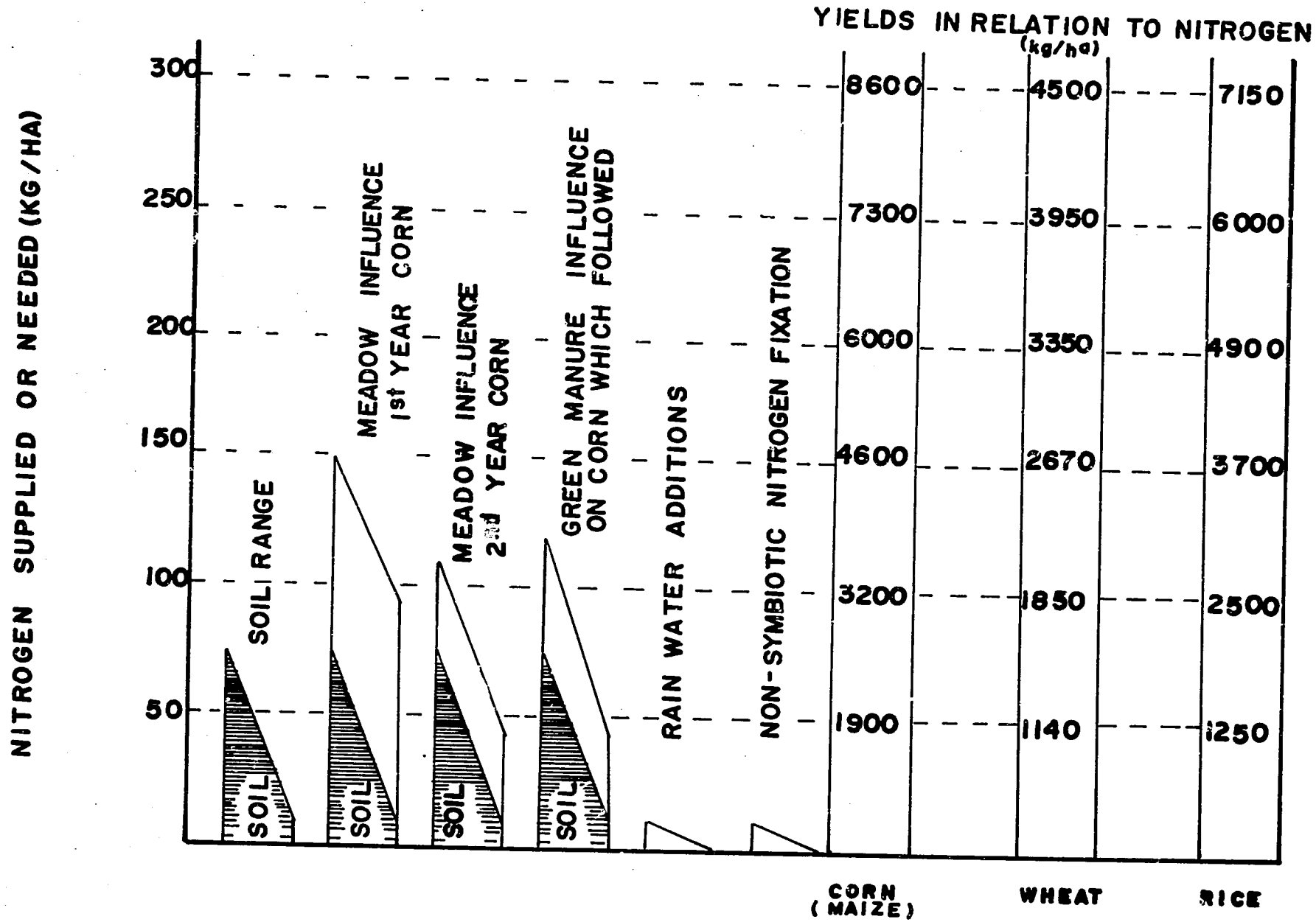

Figure 8. A comparison of the magnitudes of some supply processes with crop needs for nitrogen.

test. It is difficult to determine the degree of added precision that has been or could be achieved by the judicious use of soil test procedures over that obtained by noting traditional or check yields. Tests probably are not justified except where high precision is needed in rates of nitrogen addition and where soils are variable in organic matter and a high proportion of the crop need comes from natural supply processes.

VIII. THE BASIC SYSTEM FOR MAKING NITROGEN FERTILIZER RECOMMENDATIONS

A basic system for assessing the needs for fertilizer nitrogen by cereals is given in Tables 9, 10, and 11. Increment response information from Figures 6, 7, and 8 has been conveniently tabulated. The system requires estimates of the traditional yields, the standard or expected yields and increment responses to nitrogen applications.

All estimates can be expressed in terms of yields or of increment increases in yield. The traditional yield estimates provide collective or integrated evaluations of the natural supply processes and of nitrogen transformations processes which modify availability.

The standard yields, or maximum yields attainable at a particular soil site, are evaluations of the general production factors which limit crop growth and which may not be conveniently or economically modified by management. They represent the top yields expected at particular sites under given systems of management where fertility and normal soil cultural practices are not restrictive. Moreover, dual function models are assumed to best represent the response phenomenon. The standard yields, then, are evaluated by the yield plateau regions of the response curves for seasons of good or above average production.

Standard yields are evaluated best from the results of field experience. They may be evaluated in part from soil site and local climatic factors but the final determinations are made almost wholly from field experiments.

In view of seasonal variations, careful appraisals need be made of the traditional yields. When the average yield levels are low the estimates are not difficult. When the yield levels are medium or relatively high, several seasons of observation may be necessary to arrive at good estimates. The best estimates are those obtained in good cropping seasons.

Table 9. Nitrogen needed for the production of corn (maize). Range of need in kg/ha.

YIELD CORN IN TONS/HECTARE											
0	1	2	3	4	5	6	7	8	9	10	11	12
26 30 35	27 31 37	53 61 72	29 33 38	30 34 40	31 35 41	32 37 43	33 38 45	34 39 46	35 40 48	36 42 49	37 43 51	38 44 52
	56 64 75	82 94 110	59 67 78	61 69 81	63 72 84	65 75 88	67 77 91	69 79 94	71 82 97	73 85 100	75 87 103
		86 98 115	90 102 119	93 106 124	96 110 129	99 114 134	102 117 139	105 121 143	108 125 148	111 129 152	
		112 128 150	117 133 156	122 139 162	126 144 169	130 149 175	134 154 182	138 159 188	142 164 194	146 169 200	
		143 163 191	149 170 199	155 177 207	160 183 215	165 189 223	170 196 231	177 202 239	180 208 246		
		175 200 234	182 208 244	189 216 253	195 223 263	201 231 272	207 239 282	213 246 291			
		208 238 279	216 247 290	224 256 301	231 265 312	238 274 323	245 283 334				
		242 277 325	251 287 338	260 298 350	268 308 363	276 318 375					
		277 317 373	287 329 387	297 341 401	306 352 415						
		313 359 422	324 372 438	335 385 453							
		350 402 473	362 416 490								
		388 446 525									

Table 10. Nitrogen needed for the production of wheat (trigo). Range of need in kg/ha.

YIELD WHEAT IN TONS/ HECTARE	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
0	22 23 25	43 48 53	66 75 84	91 105 119	118 138 158	147 174 201	179 213 247	213 255 297	250 301 352	289 351 413	330 405 480	373 463 553
0.5		21 25 28	44 52 59	69 82 94	96 115 133	125 151 176	157 190 222	191 232 272	228 278 327	267 328 388	308 382 455	351 440 528
1.0			23 27 31	48 57 66	75 90 105	104 126 148	136 165 194	170 207 244	207 253 299	246 303 360	287 357 427	330 415 500
1.5				25 30 35	52 63 74	81 99 117	113 138 163	147 180 213	184 226 268	223 276 329	264 330 396	307 388 469
2.0					27 33 39	56 69 82	88 108 128	122 150 178	159 196 233	198 246 294	239 300 361	282 358 434
2.5						29 36 43	61 75 89	95 117 139	132 163 194	171 213 255	212 267 322	255 325 395
3.0							32 39 46	66 81 96	103 127 151	142 177 212	183 231 279	226 289 352
3.5								34 42 50	71 88 105	110 138 166	151 192 233	194 250 306
4.0									37 46 55	76 96 116	117 150 183	167 208 256
4.5										39 50 61	80 104 128	123 162 201
5.0											41 54 67	84 112 140
5.5												48 58 73
6.0												

Table 11. Nitrogen needed to produce brown rice. (Kg/ha of N needed to raise yields at three levels of use efficiency).

YIELD BROWN RICE IN TONS/HECTARE

	1	2	3	4	5	6	7	8	9	10
0	30 40 51	56 80 102	86 121 154	117 163 207	149 206 261	182 250 316	215 294 371	248 338 426	281 382 481	314 426 536
1		26 40 51	56 81 103	87 123 156	119 166 210	152 210 265	185 254 320	218 298 375	251 342 430	284 386 485
2			30 41 52	61 83 105	93 126 159	126 170 214	159 214 269	192 258 324	225 302 379	258 346 434
3				31 42 53	63 85 107	96 129 162	129 173 217	162 217 272	195 261 327	228 305 382
4					32 43 54	65 87 109	98 131 164	131 175 219	164 219 274	197 263 329
5						33 44 55	66 88 110	99 132 165	132 176 220	165 220 275
6							33 44 55	66 88 110	99 132 165	132 176 220
7								33 44 55	66 88 110	99 132 165
8									33 44 55	66 88 110
9										33 44 55
10										

The fertilizer response information can be expressed in terms of yield. In the tables it is listed as kg of nitrogen to increase yield by units of metric tons. Any response information can be so calculated.

The upper set of estimates (Tables 9, 10, and 11) are for situations where the crops have made efficient use of the soluble nitrogen (65 to 85 percent recoveries depending on the crop). Such use efficiencies have been obtained in many instances and appear as the kind of use effectiveness which farm operators should try to achieve.

The center set of estimates are the mean values found in the survey of the literature (page 15). They represent the average kinds of values often used in fertilizer recommendations. For example, for corn, to raise the yield from 2 to 8 tons per hectare (32 to 125 bu/a) requires 216 kg of nitrogen. This is approximately 2 lbs of nitrogen per bu increase in yield. An 8 ton corn crop actually uses about 140 kg more nitrogen than a 2 ton crop. This means that the center set of estimates involve a use efficiency of close to 65 percent.

The lower sets of values in each instance represent the high range of use additions. Here the actual use efficiency for corn and wheat is around 50 percent. These use estimates are clearly in the excessive addition range where nitrogen is added far in excess of actual nitrogen needs. These addition rates should be considered in the pollution range.

Experience will indicate whether the general use of nitrogen by crops has been efficient or inefficient for a particular soil region, climatic zone, and management system. If sufficient data are not available, the average values in Tables 9, 10, and 11 may be close approximations of the nitrogen needs.

Nitrogen use efficiency can be controlled by fertilizer management under many soil and cropping situations. Farmers should examine their management practices with this objective in mind. Maximum economic increases in yield of crop are of primary importance. Achieving efficiency of nitrogen use without sacrificing yield could contribute significantly to this end.

This system is proposed because it employs the use of the primary basic elements which determine fertilizer need; namely: 1) an integrated evaluation of the natural supply processes as assessed by the traditional yields; 2) a measure of maximum crop needs as indicated by the standard yields; and 3) an index of the nitrogen use efficiency as shown by fertilizer response functions. Many of these same basic elements could be evaluated in part by noting soil and climatic parameters. In most instances, in the use of soil parameters, however, several processes or soil factors must be collectively evaluated in order to properly assess any one of the three basic elements noted above.

The system has general application and can be used to advantage as a guide when only meager information is available. On the other hand, it can be made as precise as natural processes will permit by the accumulation of general and site specific information on soils and crop growth.

IX. APPLICATION METHODS AND THEIR IMPACT ON NITROGEN USE EFFICIENCY

The time, or times, of application, the soil position or placement, the kinds of nitrogen carriers, and the associated ammendments applied with nitrogen all have some influence on the extent of use of nitrogen by particular crops at specific soil sites and climatic regions. Most biological processes as well as nitrogen movement phenomena, which either result in loss of nitrogen from the root zone or which influence plant use processes, are not easily controlled by management techniques. For this reason, the farmer can most effectively control plant use efficiency by his choice of nitrogen carriers and by the times and methods of application.

Nitrogen is absorbed from soil by plants from positions in what is considered the root zone. Most of the roots of cultivated crops reside in the upper 10-20 cm horizon. Vertical positions within this root zone differ in the amount and activity of resident roots. Consequently, effective absorption of plant nutrients by roots also varies with depth, not only because of amount and activity of roots, but also because of soil factors. As a result, the effective absorption positions within the root zone vary with kind of soil, with crop, and with the soil water regime.

Nitrogen fertilizers need to be applied either within the effective part of the root zone or to positions where the nitrogen will be subsequently carried into that zone as it is needed by the plant.

The anticipated water movement regimes in soil largely determine the time and place of nitrogen applications. Surface application of nitrogen must generally be carried into the soil with water in order to be effectively used. These applications should be made at a time such that they can be moved downward into the root zone by the time they are needed by the crop.

If net movement of water into and downward through the root zone is rapid during a growing season, any and all nitrogen applications are likely to be poorly used. Under these circumstances slow release carriers may be most useful.

Plow down applications of nitrogen prior to planting a crop are effective only when there is little or no net water movement downward in the soil profile during the crop production season.

There are no reasons for applying nitrogen in bands in the soil unless for the convenience of application such as anhydrous ammonia or as band applications with phosphorus and potassium. Band applications do not make the nitrogen more available to the plant and in combination with potassium in sandy soils have frequently had injurious effects on seedlings.

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