

# FERTILIZERS, SOIL ANALYSIS, AND PLANT NUTRITION

D. R. HOAGLAND



All nutrients  
supplied



Zinc deficient



**Fertilizers** are important for successful farming. But a farmer meets many problems in trying to choose the right ones. The best fertilizing program for him depends on his crop and the climate as well as on his soil.

**Soil analysis** cannot be relied on, except for unusual cases, to tell a farmer the best fertilizer for his conditions. There are too many factors it does not measure. Nor is any other test available that will give the right answers quickly and easily. Field tests must also be used. The county farm advisor can often help a farmer plan a fertilizer program for a particular combination of crop, soil, and climate.

**Plant nutrition** is a study of what a plant needs and how the roots take up needed mineral elements. Recent research findings have changed some of our ideas concerning it. This circular explains what we know about it that will help farmers choose the fertilizers they need and avoid the expense of buying ones they do not need. These are the topics covered:

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# Fertilizers, Soil Analysis, and Plant Nutrition

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Farmers want to know how to fertilize their crops to get the best returns. There is no easy answer. The results a farmer gets from fertilizing depend on such conditions as soil, climate, diseases and pests, water supply, farming methods, the kind and even variety of crop. Most of these conditions affect one or more of the others; the relations are more complex than most farmers realize. Each crop on each soil in each locality is a separate fertilizer problem.

Detailed recommendations for specific crops, soils, and localities are beyond the scope of this circular. Its purpose is rather to explain general ideas of plant nutrition that may help farmers solve their fertilizer problems. It reports recent research findings in this field. It discusses how soil and other conditions affect results with fertilizers. And it points out the limitations of soil analysis and tests of soil reaction as aids in solving fertilizer problems.

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**“Plant Foods” in the Soil.** What we often call “plant foods” are certain mineral elements in the soil, such as nitrogen, phosphorus, and potassium. They are not present in the form of elements, but are in some combined form, such as salts. Plants use small amounts of these mineral elements as raw materials to build their own foods; but the bulk of the raw materials are hydrogen and oxygen from water, and carbon from carbon dioxide in the air.

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In this circular we will mainly deal with the processes by which crops take from the soil the mineral elements they need. These mineral elements are what we try to supply in fertilizers; they are often called “plant foods.” Sometimes people use this term to mean only nitrogen, phosphorus, and potassium (pot-

ash); for these are the three that soils are most often low in.

These elements do not exist free in the soil, but are in combined form. They may be in the form of salts or in any of a number of other forms; nitrogen, for example, may be in the form of complex organic matter, or calcium nitrate,



or ammonium nitrate, or many other compounds.

Mineral elements are not foods in the strict sense of the word. They are really part of the raw material from which plants build up their own foods. Oxygen and hydrogen from water, and carbon from carbon dioxide (carbonic acid gas) in the air are the other raw materials. Most of the dry matter of a plant consists of substances chiefly made up

of carbon, hydrogen, and oxygen; only a small proportion of the mineral elements are present, as a rule.

As most farmers know, plants use the energy of sunlight to build these raw materials into organic compounds, such as starch, sugar, and protein. Hence in all problems of plant growth we have to consider light, or more broadly, climate. This always affects the way crops use mineral elements.

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## Which Mineral Elements Do Crops Need?

**Nitrogen, phosphorus, and potassium are not the only mineral elements plants need. Nine more are needed, some of them in extremely small amounts, for healthy growth; and we have found that some soils are low in one or another of them. These are the mineral elements that we know crops need:**

*In small amounts: nitrogen, phosphorus, potassium, calcium, magnesium, iron, sulfur.*

*In minute amounts: boron, manganese, zinc, copper, molybdenum.*

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For a long time, investigators thought that the only elements a plant needed from the soil itself were the seven in the first list. That idea is now known to be incorrect. Crops will not develop normally unless the soil can also supply very small amounts of the elements in the second list. Figure 1 shows what happens when tomatoes are grown with no copper. Molybdenum is the latest to be added to the list; the need for it was discovered in recent research at the California Agricultural Experiment Station and elsewhere. Still other elements may be added to the list in time; but the need for them has not yet been proved. Still, if any other mineral elements are

needed for crops in general, it must be in exceedingly small amounts. Some other elements may be beneficial for some crops under some conditions. Silicon, sodium, and aluminum may be such elements; but they would not be deficient in the soil.

Most soils can supply, without special treatment, the very small amounts of boron, manganese, zinc, copper, and molybdenum that are needed. On such soils nothing would be gained by adding more of them.

But a few soils cannot supply one or another of these elements. Knowledge of this fact has cleared up some long-standing mysteries. Investigators had been trying for years to find the causes



Fig. 1. Left, tomato plant grown in the laboratory with all needed plant foods except copper. The plant on the right was grown under the same conditions except that a solution of a copper salt was sprayed on the leaves. In California, there has been no report of copper deficiency in tomato plants grown in the field; but fruit trees on a few soils show the effects of lack of copper.

of certain plant diseases that could not be traced to any fungus or bacteria or virus. Recently they have found that some of these diseases could be prevented by supplying boron, or manganese, or zinc, or copper. Sometimes the missing element is put on the soil; sometimes it is sprayed on or injected into the plant. In Australia, the failure of some crops in certain soils has been traced to lack of molybdenum.

Of special interest to many California growers is the disease known as little-leaf (or rosette) on deciduous fruit trees, as mottle-leaf on citrus; here the missing element is zinc.

Citrus, walnut, apple, and other fruit trees on some soils have a disease called exanthema. In this disease the bark of small branches has rough, corky swellings and the tip buds die, so that the tree has a dwarf, bushy look. It can be

corrected by applying copper sulfate, either on the soil or to the tree directly as bordeaux spray or by injection.

Recent evidence indicates that a few California soils cannot supply enough either of boron or of manganese for certain crops. For example, olive trees in certain areas grow better if boron is supplied.

But while a tiny amount of boron in the soil is needed for plant growth, even a little more may be toxic. Species of plants differ greatly in the amount of boron they will stand. Excess boron in irrigation waters has prevented the successful growth of fruit trees on thousands of acres in California.

Of the mineral elements in the first list on page 4, iron is the one needed in smallest amounts. Lack of iron may also cause a plant disease—chlorosis, a yellowing of the foliage. Some soils,

particularly ones high in lime, fix iron in such a way that plants cannot get enough of it, even though it is present. We are not yet sure of all of the factors involved.

Farmers sometimes ask whether they should not choose commercial fertilizers in which the elements plants need in very small amounts are present as impurities. But these elements have to be added only under special soil and crop conditions. And when they are needed, the amounts added as impurities in a commercial fertilizer may be

not nearly enough for California soils. This is because these soils generally have a high power of fixation—that is, they hold or bind the elements chemically, so that plants cannot get them. If zinc is applied to the soil to correct little-leaf, for example, from several hundred to several thousand pounds of zinc sulfate per acre may have to be used so that trees will be able to get the very small amount they need; hence farmers often apply zinc directly to the tree by sprays, injection, by driving zinc points into the tree, or other ways.

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## How Crops Get Elements from the Soil.

**Roots can absorb mineral elements from the soil after these are dissolved in the soil moisture. Recent work suggests that the roots may also be able to get some of these mineral elements directly from extremely fine particles of soil—the soil colloids. In either case, whether the crop can get them depends chiefly on soil colloids, and on acids produced in the soil by root cells and by bacteria and other microorganisms.**

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The usual theories about plant nutrition assume that a plant can take up mineral elements only after they are dissolved in soil water (the soil solution). A plant does get much of its supply from the soil solution. Nitrogen in the form of nitrate salts, for example, is nearly all dissolved in the soil water. But lately scientists have found evidence that there may be another way that plant roots can absorb mineral elements.

The other way has to do with the relations between plants and soil colloids. Colloids are very finely divided particles of matter. Because they are so small, they have a large amount of sur-

face in proportion to their total volume. With such substances, chemical reactions at surfaces become of special importance. Certain kinds of mineral elements become chemically attached at the surface of soil colloids.

According to the recent theory, when the soil colloid is in intimate contact with the fine roots of the plant, elements attached to the surface of the colloid may move directly into the root; they do not have to be dissolved in the soil water first (contact absorption). Fortunately, most of the practical deductions based on the soil-solution theory remain sound, even if the more direct method proves to be an impor-



tant way for plants to absorb mineral elements.

The soil moisture seldom has enough plant foods in it at any one time to supply the needs of crops for the whole period of their growth. For example, during the season a crop may remove from the soil many times the amount of phosphate that is dissolved in the soil water at the beginning of the season.

Whether the crop can get enough of the needed mineral elements from the soil solution, then, is a question of how fast they dissolve in the soil water. If they do not dissolve as fast as the plant takes them up, growth may be limited. If one element is lacking, growth will be limited, even if there is plenty of all the others.

Some of the mineral elements dissolve very slowly unless acids are present. Acids are produced in the soil by root cells of plants and by bacteria and other microorganisms. In most California soils these acids are neutralized by basic substances in the soil as fast as they are produced. The neutralizing of the acids by basic substances produces salts, some of which contain the mineral elements plants need. Most of these salts dissolve in the soil water, where plant roots can absorb them.

Bacterial action is particularly important in making nitrogen available. The nitrogen present in organic matter is in an insoluble or unsuitable form, and plants cannot absorb it. Bacteria may bring about the production of nitrate salts from this organic nitrogen, and thus make it available to plants. The nitrate salts also contain calcium, magnesium, or potassium, which are then made available in this way. The activity of these bacteria and other microorganisms depends on organic matter. Organic matter thus plays an indirect part in dissolving some of the plant foods.

In view of the direct action of root

cells described in the next paragraph, plants may be able to get along without this particular action of organic matter (if nitrogen is supplied in some other form). But organic matter is valuable in other ways (see page 16). If for any reason organic matter increases root growth, mineral elements will be absorbed faster; and in this sense also organic matter helps to make them available.

We have mentioned that acid is produced by root cells. Most investigators think that the only acid given off by roots is carbonic acid; but perhaps others are given off by some kinds of plants or under certain conditions (see page 11). The carbonic acid given off by roots is very important because of the very close contact between fine roots, or root hairs, and particles of soil colloids. In this way, mineral elements are dissolved very close to the roots that absorb them. The acid can readily displace potassium, calcium, magnesium, and sodium from some mineral or organic compounds of the soil. Hence these elements can be absorbed more rapidly, whether they go directly from the soil colloid to the root, or first dissolve in the soil water.

A plant is not like a lamp wick that takes up whatever liquid it is placed in. Roots do not just take up the solution they find in the soil. They may absorb mineral elements faster or slower than they absorb the water—usually slower. They may take one mineral element faster than another. Plants, therefore, have a selective action. But this does not mean that they can select only the elements they need for growth and reject all else. On the contrary, the roots often absorb elements that plants do not need or can get along without, like sodium; harmful substances may be taken up by roots if they are present in the soil; and needed elements may be taken up in larger amounts than are needed, even in harmful amounts.

## Root Growth Affects Elements Absorbed.

Whatever affects root growth affects the rate at which roots absorb mineral elements from the soil. To grow well, roots need air; and the air supply of the roots depends on the way a farmer manages his soil as well as on the kind of soil. Also, anything that prevents good top growth will slow root growth.

The total area of root surface (in a good plant this is enormous) partly determines whether a crop can get enough of the needed elements from the soil. The plant is affected not only by the kind of soil it grows in but also by the amount of soil available to it. Hence it is important for farmers to keep the soil in good condition for root growth.

Roots grow and absorb mineral elements only by the activity of living cells; and these cells will not be healthy and active if they do not get enough oxygen. Roots need air (fig. 2). Many irrigation and cultivation practices that farmers use affect the air supply in the

soil and are thus definitely related to the supply of mineral elements roots can absorb. This will also depend on the amount and kind of clay in the soil.

Poisonous substances of any kind, and injurious bacteria or other microorganisms, interfere with root growth and hence with the plant's supply of mineral elements.

Because the substances needed for root growth are made in the leaves, top growth also affects root growth. In this way, climatic conditions, diseases, injuries, even fruit production, may affect root growth and hence the mineral elements the plant can get from the soil.

Fig. 2. The tomato plants on the left were grown in a complete nutrient solution with air bubbled through it; those on the right were grown in the same solution without aeration. Air in the soil is as necessary as in the nutrient solution.





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**Some Soils Fix Potassium.** Most California soils have enough potassium in total amount. Most of them have enough of it in a form plants can use. But a few of them hold potassium so firmly that plant roots cannot absorb enough of it. Such soils (not very common in California) may need potassium fertilizer even though they have high potassium content.

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In most California soils the total amount of potassium is ample. Then, if enough acid is produced by microorganisms and roots, will crops always be able to absorb potassium fast enough for good growth? That depends on the kind of compounds in which the potassium occurs. Some potassium compounds do not dissolve very easily. Some potassium is chemically bound to or attached by soil colloids in such a way that roots find it hard to absorb. In other cases potassium may be bound to the colloid less tightly so that the roots in contact with the colloid can easily get it.

Tests with dilute acids (such as  $\frac{1}{4}$  per cent nitric acid) give some idea of how much of the total potassium will dissolve easily in the soil water or in the acids given off by plant roots or by microorganisms. The amount that dissolves in dilute acids is only a small fraction of the total potassium in the soil. Still, these and other tests show that most California soils can supply enough potassium for plant growth, either from the soil solution or directly from certain colloids.

The amount of potassium easily available to plants is more important to farmers than the total amount in the soil. But if the potassium minerals are finely divided, a high total amount may be of some benefit; for it gives roots more chance to come into contact with potassium compounds.

Even if a soil is low in the easily soluble forms of potassium, crops may not suffer from lack of potassium. Some crops may still be able to take enough potassium from the soil for an indefinite time. Plants with a large area of actively absorbing root surface and a long growing season may be able to get along, even in soils that have very low amounts of potassium in the soil water. Of course, if the potassium-supplying power of the soil falls too low, even this kind of plant will not thrive unless the soil is fertilized with potassium.

A potassium fertilizer is often needed in humid regions, where many soils are low in available potassium. It is not often needed in California; but a few soils here are now known to be low in available potassium. Dieback, a disease of prune trees on some California soils, has been traced to a lack of potassium.

Plants differ not only in the amount of potassium they can get from a given soil, but also in the amount they need. According to most agriculturists, plants that produce large amounts of starch or sugar have high potassium needs; but just why this should be so is not fully understood. Some of these plants are thought to yield best on soils that have large amounts of potassium in easily available form. These ideas are based chiefly on experience in other parts of the world. We do not yet know whether such crops respond to a potassium fertilizer on most California soils.

Some tests seem to show that they do, in a few soils; but in many soils they do not.

Light and temperature may affect the amount of potassium a crop needs. Another factor is the amount of seed borne, or especially the amount of fruit borne by fruit trees. Studies have shown that age of trees, rootstock, amount of fruit borne, and climatic conditions

are important factors in prune dieback.

Certain parts of the plant will contain more potassium if enough potassium fertilizer is used—unless the soil can already supply all the potassium the plant can absorb. But beyond a given percentage, the added potassium in the crop is just excess; it does not increase growth or improve quality—in fact, it may be harmful.

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**Other Soils Fix Phosphorus.** Phosphorus, like potassium, may be fixed by some soils so that plants cannot get it. Fertilizing such soils with phosphorus will not help much unless it reaches the absorbing roots in a form they can absorb. Plants differ greatly in their ability to take phosphorus from such soils.

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Ordinary soils have much less total phosphorus than potassium; and the chemical reactions of the two are very different. But with both, the percentage of the total that plants can absorb varies greatly from soil to soil. A comparison of two California soils with about the same total amount of phosphorus illustrates this. Almost no phosphorus was dissolved from one soil by a dilute acid; while from the other, treated in the same way, more than half was dissolved. Many (but not all) crops make a poor growth in the first soil because they cannot get enough phosphorus; but there is no lack of it in the second.

The question is more complex than this example implies. Some evidence suggests that there are two classes of phosphorus compounds in the soil: (1) those which dissolve readily in dilute mineral acid; and (2) those which do not dissolve readily in dilute acid but are released into alkaline solutions; this involves special chemical reactions of soil colloids.

Whether plants can absorb the phosphorus held by colloids depends on how much phosphorus is in this form. The greater the amount of this phosphorus in proportion to the amount of colloid, the easier it will be for plants to absorb.

Sometimes the availability of phosphorus depends on the ability of the soil to neutralize acids (produced by roots or soil bacteria) as they are formed (this ability is called buffering capacity). If this is high, plants may be prevented from getting the phosphate that would otherwise dissolve in dilute acid at root surfaces. This is apt to happen in a soil that has a large amount of lime.

In some types of soil that are high in iron or aluminum or in a mineral colloid called kaolinite, phosphorus is only slightly available to plants. This is because the phosphate is bound up with these substances in compounds; and in these forms it does not dissolve readily, even in such acids as would be present in the soil.

Again as with potassium, crops differ greatly in their ability to get phosphate from soils that are low in easily soluble phosphate. Crops with a large absorbing root surface and a long growing season have an advantage. Some of the difference may be due to organic acids (other than carbonic acid), if they are given off by the roots of certain species of plants; some of these acids can displace phosphate from colloids high in iron or aluminum.

Fruit trees can often get enough phosphate from soils low in easily soluble phosphate—soils in which most annual crops might fail for lack of phosphate unless fertilized with it. There is little evidence that fruit trees in California

respond directly to phosphate fertilizer, even when some other crops in the same soil may show large response. But if a covercrop responds to this fertilizer, the tree may benefit indirectly.

This discussion may indicate how many things must be considered in deciding whether to try potash or phosphate fertilizers. The need for them is determined not only by the soil type, but by crop, soil conditions that affect root growth, the amount of organic matter in the soil, and climate.

Soils that cannot supply enough potassium or phosphorus in the first place may have unusual power to fix one or the other of these applied in fertilizers; this is discussed on pages 13 and 14.

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**Need for Nitrogen Fertilizers.** Nitrogen is the element that most often gives good results in fertilizing California soils, except when legumes are grown. It can easily be leached out of the root zone or lost to the air by the action of soil bacteria.

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Sooner or later, some type of fertilizer is needed for most farm crops. Legumes, such as alfalfa and peas, fix nitrogen from the air. When legumes are included in a crop rotation, the most important needs in many regions are for phosphate and, in acid soils, lime. But in general, farmers everywhere are especially concerned about keeping up the nitrogen supply in the soil. Crops do not always respond to nitrogen; but they do respond under many soil, crop, and climatic conditions. Many crops need a great deal of nitrogen.

When nitrogen is in the form of nitrate, it dissolves very readily in the

soil water; and it is easily leached out of the root zone by rain or irrigation water that penetrates deeply.

Nitrogen may also be lost as a gas. Some soil bacteria change the nitrogen in organic matter to nitrate; then others, under some conditions, may change it in part to nitrogen gas. Plants cannot use it in this form, and it is lost to the air. Experiments at Berkeley show how heavy this latter loss may be. The nitrogen content was studied in thirteen soils from different parts of California over many years. They were placed in containers and irrigated carefully to prevent leaching; some con-



tainers of each soil were cropped to barley and some were left uncropped. The loss of nitrogen by the action of bacteria was found to be greater than the amount removed by the crop. The large losses of nitrogen occurred in the earlier years of the experiment, when large amounts of nitrate were present in the soils in the spring. After several years of cropping, these soils reached a low level of yield, and a low content of nitrate; but the total nitrogen in the soil changed only slightly after that.

The amount of nitrogen and total organic matter in a soil depends on climatic conditions. When there is plenty of water and oxygen in the soil and soil temperatures are high, the nitrogen in added organic matter is rapidly changed to nitrate and may be partly lost by leaching; and perhaps some of the nitrogen may be lost as gas to the air.

On the other hand, some nitrogen is fixed from the air by free soil bacteria or by legumes with root nodules. The latter is particularly important to farmers.

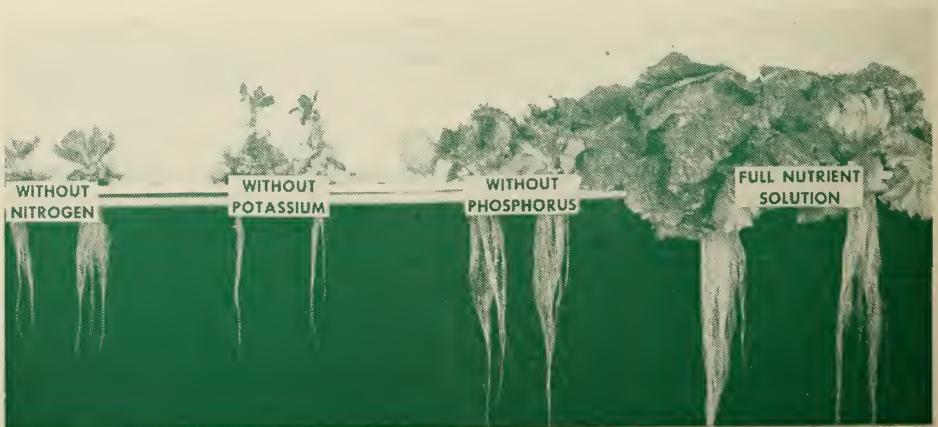
The nitrogen in the soil at any time is the net result of the gains brought about by bacteria and the losses from crops, leaching, and bacterial action.

Much more work must be done before we understand fully what happens to nitrogen in the soil; but we know that nitrogen losses from the soil may be great under some conditions.

These facts may help to explain why adding nitrogen to the soil so often gives good results. This is true whether it is done by growing legumes or by using animal manure or commercial forms of nitrogen.

Whenever a farmer has nitrogen problems to deal with, it is most important for him to consider the activities of soil bacteria, and how his irrigation and cultivation methods and any additions of organic matter may affect them. Adding organic matter with too high a ratio of carbohydrate to nitrogen—for example, cereal straw—causes a temporary loss of available nitrogen (nitrate). This is because the carbohydrate causes the soil bacteria to multiply rapidly; and while they are doing this, they use up the nitrate. For some time the crop may suffer from lack of nitrogen when this happens, unless a large enough amount of nitrogen fertilizer is also applied. In the end, however, the carbohydrate may enable the soil bacteria to add a small amount of nitrogen to the soil from the air.

Fig. 3. Lettuce plants grown in nutrient solutions lacking only nitrogen, or potassium, or phosphorus, and (right) in nutrient solution containing all needed mineral elements.



**Soils React Chemically with Fertilizers.** The final result of adding fertilizers depends on the way the soil reacts with them. The same fertilizer will produce different effects in different soils. In some soils, much of the phosphate and potash added may be fixed in the upper layers. Nitrogen in the form of ammonia is also fixed by the soil, but only temporarily.

People often speak of "balanced fertilizers." But the balance that is important to the farmer is not the balance in the fertilizers; it is the balance in the soil after the fertilizer has been added.

We have seen that the potassium and phosphorus in some soils are held so tightly that plants cannot get enough of them. The same soils may also fix potassium and phosphorus added in fertilizers.

Potassium (potash) reacts chiefly with soil colloids. In this reaction some of the potassium added may be fixed (attached to the colloid); it goes out of solution, and calcium or magnesium goes into solution to take its place. Generally, in fairly heavy soils, nearly all the potassium added in an ordinary fertilizer application is fixed in this way.

Phosphorus (phosphate) will also be changed when it is added to a soil, but chemically the reactions are not the same as with potassium. Phosphate that is easily dissolved in water before it is added to the soil becomes much less soluble afterward.

In some soils part of the potassium or phosphorus is fixed so firmly that roots cannot get much of it, even if they are close to the soil particles it is attached to. This is especially true of phosphorus, and seems to occur faster with some kinds of phosphate fertilizer than with others. It also depends on how the phosphate fertilizer is applied, whether

locally close to the roots, or mixed throughout a large mass of soil.

Other soils do not hold the potassium or the phosphorus so firmly. Roots can then absorb the element if they are close to where it is held. This has been shown on some California soils that have a high fixing power for one or the other of these elements. On these soils, some crops made almost no growth because the mineral element naturally present was not in sufficiently soluble form, nor easily available from the colloid. When the element that was lacking was applied as a fertilizer, shallow-rooted crops made good growth. Wheat, barley, tomatoes, and beets, for example, responded well to potash fertilizer in pot tests. With phosphorus, the form of phosphate used and the way it was applied to the soil was important in getting good results.

The plant is an active agent in the process. With potassium, this is because the root cells give off carbonic or other acids (see page 11); and also because the potassium is quickly removed from the soil water or the soil colloid by the growing plant. The way plant roots absorb phosphates in such cases is not well understood as yet. With some methods of application, roots may make direct contacts with particles of unchanged phosphate fertilizer, when this is not so soluble as to be toxic. The finely divided and reactive nature of the compounds formed when phos-

phate is added to the soil may be important.

The fixing of potassium and phosphorus in the upper layers of the soil is very important when farmers fertilize fruit trees under California conditions; for the added mineral element may be out of reach of most of the absorbing roots of the tree. In soils of high fixing power, it is difficult—and may not be practical—for farmers to increase the potassium or phosphorus available to roots very far below the surface. Some investigators have reported a few good results with potash fertilizers applied below the surface in certain prune

orchards; but these were probably unusual cases. With phosphorus, the farmer may sometimes succeed in getting good penetration by using very large amounts of fertilizer, by applying it in special ways, or by the effects of organic matter.

Nitrogen in the form of ammonia nitrogen is also at first fixed by soil colloids. But then soil bacteria convert it to nitrate, which readily dissolves in the soil water and moves downward. Thus fixation makes it unavailable to plants for only a short time. Nitrogen in the form of nitrate does not become fixed, even briefly.

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## What to Consider in Choosing Fertilizers.

**A farmer should consider soil, crop, climate, and previous farming history in deciding on his fertilizing program. Sooner or later, if land is cropped year after year, some fertilizer will be needed. Nitrogen is the element likely to be needed first on most California soils. In many soils, crops may not respond to potash or phosphate fertilizer until after the soil has been farmed for many years without adding them in any form. Other elements may be needed for certain crops on certain soils.**

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From what has been said already, we see that the results a farmer can expect from applying fertilizers depend on many things. They depend on the soil—whether it has high fixing power for potassium or for phosphorus, how much plant food has already been taken from it by crops; what its physical condition is. They depend on the crop to be grown—how deep-rooted it is; how large a root system it has; how long its growing season is; whether it has special demands for a given plant food. They depend on the form of fertilizer

used, and the way it is applied. They depend on climate.

Many soils may stay productive for a long time if a farmer adds only one or two of the three mineral elements nitrogen, phosphorus, and potassium. A farmer may keep his soil balanced for crop growth, at least for many years, by just adding nitrogen in the right form; this of course is provided he has a soil well enough supplied in the first place with the other elements, including those needed in very small amounts; and provided that by proper soil man-



agement he keeps the soil in good physical condition.

But of course we must recognize that continuous and intensive cropping tends to lower the amount of easily available phosphate or potassium; and that this may happen even in soils that have high fertility to start with, as many California soils do.

The question a farmer must ask is: Has my soil reached the point where it needs a phosphate or potash fertilizer, or will it reach this point soon? The answer depends on the crop as well as the soil; for, as we have seen earlier, some crops can get potassium or phosphorus from compounds that do not dissolve easily; and most soils have plenty of such compounds, in comparison with the amounts plants need.

If a crop does not do well, some other element may be lacking, rather than potassium or phosphorus, or even nitrogen. Sulfur may be lacking; this has been found true of a number of California soils when legumes are grown.

Iron may be low (see page 5); or copper or boron or manganese or zinc (see page 5). In humid regions, magnesium is sometimes found to be lacking, especially on sandy soils; but few studies have been made on magnesium deficiencies in California. Calcium deficiency is discussed on pages 20 to 21.

However these questions are answered for a given soil at a given time, we know that a soil will not stay productive forever if it is cropped year after year and no fertilizer is added. A farmer may add the needed mineral elements in various ways. He may use covercrops, animal manure, nitrogen or other commercial fertilizers; or he may need to use some combination of these. He may apply one of the elements needed in very small amounts directly to the plant, by sprays or in other ways. In choosing his fertilizer, he should consider the physical state of the soil and also how the soil bacteria are operating. And of course there is always the question of comparative costs.

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**Manure or Commercial Fertilizers?** *Manure is valuable; but it is not always the most satisfactory or economical way to supply needed plant foods. Even if it were, there is not enough of it for all the soils that need fertilizing. Commercial fertilizers, with proper soil management, may often give as good results as animal manure.*

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When a farmer puts large amounts of animal manure on his soil year after year, he adds not only nitrogen but also considerable quantities of potassium and phosphorus. From earliest times people have observed that animal manure produces very good effects on plant growth.

For about one hundred years the Rothamsted Experimental Station in England has compared animal manures and commercial fertilizers. Several years ago the Station reviewed its results up to that time. Experiments on plots that had been continuously cropped to wheat showed that yields

were about the same for plots fertilized with commercial fertilizers and with animal manure.

The organic matter of manure is valuable in some soils because it helps to maintain a good physical condition. But other forms of organic matter (such as covercrops) may do the same thing. Also the methods a farmer uses in cultivating and irrigating have a very important effect on the physical condition of the soil.

Some people have suggested that animal manure or other organic matter may contain hormone- or vitaminlike substances that are good for crops; or else that it may cause microorganisms to produce them. But there seems to be no good evidence that such an effect is

of any practical importance for crop plants under farm conditions. These plants themselves manufacture all the organic substances they need for growth. All the soil does is to supply mineral elements, water, and air to the roots, and to provide anchorage for the plant.

Although some farmers may solve their own problems of soil fertility by using manure, this is not the solution for all farmers. Often not enough manure is available. And if manure is produced on one soil and applied to another, how are the mineral elements produced on the first soil to be replaced? In an agricultural area *as a whole*, some kind of commercial fertilizers will have to be used in the long run for continued production of good crops.

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## What Part Does Organic Matter Play? Crops

**do not require organic matter in itself. But the indirect effects of organic matter may be extremely important.**

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In experiments, many crops have been grown successfully without organic matter. They have been grown in nutrient solutions, or in pure sand to which only mineral elements have been added. These experiments show that organic matter in the soil is not absolutely necessary for crop growth.

But under field conditions, organic matter has many indirect benefits in plant nutrition. Some of these have been mentioned. It may serve as a

source of nitrogen or other mineral elements. It is needed for the growth of microorganisms that help to make mineral elements available to crops; for example, it may help to make phosphorus and iron available. Through its effect on the physical condition of the soil, it aids in soil aeration and thus promotes healthy growth of roots. An understanding of the part it plays will help farmers to get the best results from their fertilizing program.

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**Covercrops and Crop Rotation.** Covercrops furnish organic matter; and in this and other ways build up the supplies of easily available potassium and phosphorus, and, especially if they are legumes, of nitrogen. Farmers have learned from long experience that crop rotation is sound practice wherever it is practical. But sometimes, by proper fertilizing if this is needed, the same crop has been grown successfully for very long periods in the same soil.

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Turning under covercrops may tend to build up the soil reserve of easily available potassium and phosphorus. Covercrops do this partly through the effects of the organic matter they furnish. But also they gradually accumulate potassium and phosphorus from very slightly soluble compounds present in the soil, including the deeper zones; and when they are turned under, all that they accumulate in their tissues may remain at least temporarily in an easily available form in the part of the soil where they decompose.

We do not yet know how important these effects are in California soils. Plants grown on soils that contain very small amounts of available potassium or phosphorus are apt to have rather low percentages of these elements in their tissues. Hence covercrops might not be able to build up the available supplies of them to any large extent in such soils. Then, too, the power of some soils to fix potassium and phosphorus tends to limit the building up of a supply of these elements in available form.

Covercrops are also important for the organic matter they furnish. How this aids soil aeration, water penetration, and the growth of useful bacteria, and builds up the supply of nitrogen was mentioned in the previous section.

Crop rotation has proved its value in farming. In many parts of the world where crops have been grown much longer than here, farmers have often found that growing one crop continuously gives very poor results. Through long field experience, they have worked out suitable rotations of crops, including legumes; they often use phosphate, lime (if the soil is acid), or other fertilizers along with the rotation.

There are many benefits from crop rotation: Legumes in the rotation help to keep up the soil supply of nitrogen. Different crops vary in their needs of given mineral elements and also in their ability to absorb different mineral elements, especially potassium and phosphorus; and these differences help in making the best use of the minerals in the soil. Other benefits are less directly connected with plant nutrition. Crop rotation helps to prevent the building up of injurious soil microorganisms and of plant disease. It avoids the toxic effect that the residues of some crops may have on the same crop grown in following years.

Some farmers have grown the same crop successfully for many years by using enough animal manure, or commercial fertilizers, or both. But in general, rotation of crops is sound practice wherever it can be used.



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## How Does Fertilizing Affect Crop Quality?

Not too much is known about the effects of fertilizers on crop quality under California conditions. Fertilizers are most apt to improve quality if they supply an element that the soil cannot supply enough of. Too much nitrogen may lower quality in some fruit crops. No fertilizer can be expected to improve quality in all crops or on all soils.

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Under some soil and climatic conditions, the quality of crops may be influenced by fertilizer applications. Quality is improved mostly in soils that before fertilizing could supply very little of one or more needed mineral elements. Many of the reports about the effects of fertilizers on crop quality are based on experiments under different soil and climatic conditions than those in most parts of California.

There has been much discussion about the possible effect of potassium or phosphate fertilizers on crop quality (as distinct from yield). Many observations show that fertilizers applied to deficient soils may change the rate of growth or time of maturity of various crops. For example, phosphorus, applied to soils deficient only in this element, may make roots develop faster and increase tillering and grain formation in cereals. Cereals seem to have a special need of available phosphorus in their early stages of growth. Again, adding potassium to a soil low in available potassium tends to produce plumper seeds in cereals. None of these effects will result if the soil already has enough available phosphorus or potassium.

With fruit trees or vines, it is hard to get clear-cut answers about the effects of potash or phosphate fertilizers on fruit quality under field conditions in California. Most California investiga-

tors have reported negative or inconclusive results; but the question is still being studied. Some definite observations have recently been made on fruit quality in citrus trees grown in sand cultures; but their practical application has not yet been worked out.

Yield or quality, or both, may be affected by soil conditions that produce disease. They may, for example, be affected in prune dieback, which is partly due to lack of available potassium in the soil of certain districts. But most plant diseases are not due to lack of phosphorus or potassium.

Field observations in various parts of the world have sometimes seemed to show that lack of potassium makes plants less resistant to certain bacterial or fungus diseases. This is a subject of great interest. Unfortunately, the work of investigation is very complicated; and we do not yet have enough working knowledge. A marked deficiency of a needed element leads to an abnormal change in the composition of plant tissues; and this may make the plant more susceptible to attack by bacteria, fungi, or insects. On the other hand, excessive use of nitrogen may produce a succulent plant of low resistance to some diseases.

Aside from any relation to disease, excessive nitrogen applications may lower commercial quality in some fruits. This happens even though there

is plenty of available potassium and phosphorus in the soil. How much nitrogen is "excessive" depends on the kind of crop and on the climate, including sunshine.

"Quality" is a very general term. Sometimes a claim is made that a given fertilizer will improve quality. Such a claim does not mean much unless it tells

just what effects on quality the fertilizer produces, and on what crop.

Climate and the inherited characteristics of the plant may be more decisive in crop quality than soil management and fertilizers, important as these may be. And insect injury or bacterial and fungus diseases often have more effect on quality than anything else does.

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**Minerals and Vitamins in Crops.** Sometimes crops grown on a soil low in some mineral element will not have enough of that element for the needs of animals, especially grazing animals. But varied foods, especially in human diets, usually take care of any such lack in one crop. Also, the seeds and fruits of a crop tend to have a fairly constant mineral content. Climate and the kind and variety of plant often have more effect on the vitamins in a crop than the soil does.

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How does the supply of mineral elements in a soil affect the mineral and vitamin content of crops grown in it? Will fertilizers affect this content, and thus improve the nutritional value of the crop for human and animal nutrition? These questions have recently been receiving much attention. The subject is being investigated at a federal laboratory at Cornell University. The questions are complex, and complete answers will take years of scientific study. Some statements about this subject in newspapers, popular journals, or "health books" do not have an adequate scientific basis and may be misleading. Farmers can get reliable information, so far as it is available, from publications of the federal government, state experiment stations, or recognized institutions of medical research.

Some plant products grown in cer-

tain soils may be nutritionally deficient in one or more mineral elements needed by animals or humans. Deficiencies of calcium, phosphate, iodine, iron, manganese, copper, and, rarely, cobalt, have been reported. (Iodine and cobalt are not needed by plants; but animals need them, and small amounts are usually present in plant tissues.) But when the food products consumed are varied and come from many sources, there are not likely to be serious deficiencies in diet.

Then, too, the plant tends to keep a fairly constant composition in its fruits and seeds. Fertilizers, used in ordinary amounts, make rather small changes in this composition. For example, a tomato fruit cannot be made a rich source of calcium by fertilizing the soil; in this respect it will always be inferior to milk. To say that a tomato has been "mineralized" is misleading.

Greater changes may be found in plant leaves and stems. But even with these, it is not always easy to bring about a change. A plant is not apt to be low in such elements as iron, copper, or manganese unless the soil has a high fixing power for them; and if it has, adding a little of them to the soil may not increase them in the plant, as we saw earlier (page 6).

Many claims have been made that increasing a given element in the soil

may increase the concentration of some vitamin in plants. Evidence so far suggests that light and other climatic factors may be more important in the amount of certain vitamins in the plant than will the soil supply of mineral elements. This is rather definitely known to be true of vitamin C. The vitamin content of a plant may also vary widely with the variety grown, even when soil, climate, and all other factors are constant.

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**Acid and Alkaline Soils.** A farmer can seldom tell from the soil reaction alone whether his soil is too acid or too alkaline for a given crop. He should consider other characteristics of the soil before he decides whether he needs to use lime or any other substance to change the soil reaction.

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When we speak of an acid or alkaline soil, we are generally talking about the reaction of the soil solution. (But some measurements of acidity or alkalinity show any effects the soil colloids may have, as well as the reaction of the soil solution.) The reaction of the soil solution will vary to some extent with the amount of water and carbon dioxide in the soil, and other things. A neutral reaction is one that is the same as that of pure water. The symbol pH is used to indicate acidity or alkalinity: pH 7 means a neutral reaction; pH below 7 means an acid reaction, pH above 7 an alkaline one. A soil of pH 5 is decidedly acid; one of pH 9, decidedly alkaline. A great many soils in California have reactions close to the neutral point.

Markedly acid soils are common in some regions; they may be found in those areas in California that have a high rainfall. Elsewhere in the state

they are not very common among important agricultural soils.

Highly alkaline soils occur in many parts of California; but the problem of alkali conditions associated with the high alkalinity is outside the scope of this circular. It is discussed in other publications of the Station.

The soil reaction may reflect the amount of calcium in a soil that is fixed by soil colloids. A very acid or very alkaline soil may be unfavorable to plant growth partly because it cannot supply enough calcium. Acidity or alkalinity may also affect the amount of iron, manganese, or phosphate that is available to plants.

Certain substances added to the soil will change its reaction. Thus, sulfur and sulfate of ammonia both tend to increase acidity, or decrease alkalinity. Nitrate of soda (sodium nitrate) tends to lessen acidity, or to increase alkalinity. These changes are associated in



part with the activities of microorganisms or of plants; and with the chemical changes in the soil that result. Lime decreases soil acidity by direct chemical reaction with the soil.

Unless the soil is light or sandy, it is hard to change its reaction much in a few years by using ordinary fertilizers.

Most crops will grow well in soils with a rather wide range of reaction. An acid soil is not necessarily unproductive. For example, some rather acid peat soils, when properly fertilized (but still acid) are very productive. The reaction, or pH, of a soil is merely one

factor that affects growth. Important as it is at times, a farmer should seldom or never rely on it alone as a guide to understanding soil conditions.

For these and other reasons, there is no sound basis for trying to list plants according to the degree of acidity or alkalinity they prefer. Some plants that were formerly thought to prefer alkaline soils also do very well on certain kinds of acid soils. Each soil demands study of all the factors involved. Merely measuring one value of the soil, such as pH, may lead to wrong conclusions under California conditions.

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## Why Soil Analysis Seldom Helps Farmers.

**Under California conditions, routine soil analysis cannot be relied on to tell a farmer the best fertilizer for a soil, or whether a soil is suited to a certain crop. There are too many factors that the chemical analysis cannot measure. Besides, the soil varies so much that it is very difficult to take a small sample that properly represents a large area.**

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Perhaps from what has already been said it will be clear why routine chemical analysis alone cannot often determine what crops a soil is suited to, or the best method of fertilizing it. True, chemical methods are needed for special investigations on soils, and the understanding of general principles. But really adequate methods are costly. They can be carried out by the Experiment Station only in selected cases, to obtain knowledge of general relations or to aid in planning or interpreting field experiments. Any conclusions based on chemical data must in the end be checked by field experiments.

If we had chemical methods that would give us the right answers in

terms of crop growth, there would still be the problem of getting representative samples. Even in a field that looks uniform, the soil may vary considerably. Hence it is hard to select samples that represent the average condition. Then there is the question of the importance of soil samples taken from different depths: the mineral elements available in the upper soil layers will be more important for shallow-rooted crops; those in the lower soil layers for deep-rooted crops. It is also important to know whether moisture conditions are favorable where the mineral elements are available.

Some of the difficulties with soil analysis come from variations in the

soil solution. In one common type of chemical analysis, the soil is extracted with water. We can thus find what elements are in solution at that time. But the soil solution varies, even from day to day. If crops have been growing rapidly, they may have temporarily used up some of the elements dissolved in the soil water. With methods of this type, therefore, results will be different at one time of year than at another. The supply of available nitrogen depends on the activities of soil bacteria; and we cannot tell much about these in a single simple test.

On a few soils a routine soil analysis may strongly suggest that potassium or phosphate is deficient; but such soils are often so badly deficient that the trouble can be recognized by practical observations, without a soil analysis.

Most soils that California farmers ask to have analyzed are neither badly deficient in any mineral element nor outstandingly fertile. Often the trouble may be of a kind that has little to do with deficiencies of mineral elements, such as the presence of disease, lack of water, presence of alkali. These are just the soils on which an interpretation of a soil analysis for fertility is likely to

fail of its purpose. The main successes of soil analysis are with soils either extremely high in a plant food, or else extremely low—soils in which the need for any analysis is not pressing.

In some states that grow comparatively few crops, have comparatively few soil types and a fairly uniform climate, and have more experience with field tests, soil analyses are widely used. The great diversity of soils, crops, and climate in California makes the problem of interpreting chemical tests on soils far more complex and uncertain here.

Before there can be more general application of chemical tests here, there must be careful comparison between the chemical-test results and the growth of different crops, with and without particular fertilizers, on these soils under carefully controlled conditions. We also need more critical study of field experience in California.

A careful survey of soils is being made to learn how to interpret and apply new chemical and biological tests. Special attention is being given to questions of potassium and phosphate availability in California soils. Eventually the results of field experiments should show whether these tests are useful.

Fig. 4. Choosing a sample for plant analysis. The part of the plant chosen is important for good results with this method, and varies with the crop.



**Plant Analysis.** The plant itself reflects all the complex factors that affect its nutrition. Then, by analyzing the plants grown on a soil, can we find out what elements, if any, the soil is low in? An investigation is now being carried out on this method. We must find out for each crop what part of the plant to sample. To interpret the results, we have to take account of standards for the crop, and the period of growth when the sample is taken.

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Recently there has been much interest in the possibility of finding what elements a soil cannot supply adequately by analyzing the plants grown on it. The method is called plant analysis, or foliar diagnosis. Usually the whole leaf, the stem, or the leaf stem is analyzed for the elements being studied. So far, special attention has been given to nitrogen, potassium, and phosphorus.

The method is based on the idea that the plant is the best index of the complex system of soil, plant, and climate. A plant that is not suffering from the lack of some element should have in its tissues at least a certain low percentage (critical percentage) of each mineral element that is needed for its growth. If the plant has less than this of a given element, it is probably at least somewhat starved for that element.

The critical percentage cannot be fixed at any one exact point. For each element there would be a narrow range of values on the borderland; within that range we couldn't be sure whether or not the plant was getting enough of the element. But below that range a deficiency would be indicated for the crop under study. The critical range would be different for each crop and each mineral element. Careful study would be necessary to establish standards with which any new set of data could be compared.

Samples taken in a haphazard way would have little value. We have to know what part of the plant is apt to give the most reliable results. Above all, we have to know at what stage of growth samples should be taken. The earlier the stage of growth in which a low value appears, the more likely it is that the element is really deficient. With some crops or under some conditions, samples may have to be taken at several different stages.

At present it would be premature to use this method as a general service method. It is still under study to determine whether it has practical value as a general means of diagnosis.

One purpose is to help select soils in which there is a probability that one or more mineral elements are deficient. Then appropriate fertilizer tests can be established on these soils. This is less expensive than to make fertilizer tests in a hit-or-miss fashion. Sometimes plant analysis gives such a strong indication that the soil is able to supply plenty of a given mineral element that we do not need to test further for that element. As with soil analysis, plant analysis is most successful when soils are either extremely high or extremely low in some element; and these are soils that scarcely need special tests to reveal the situation. But this method avoids some of the other difficulties with soil



analysis and promises to be more useful when fully worked out.

Sometimes a crop does not respond to a certain mineral element applied in a fertilizer, even though there is reason to suspect that the crop is not adequately supplied with that element. Plant analysis is then useful to find whether or not the crop actually absorbed the element from the fertilized soil. There are several reasons why it might not: the mineral element might be fixed by soil colloids; the plant roots might be injured by alkali conditions or by plant disease; and the like.

Often the increased growth of a crop after nitrogen is applied may lead to a deficiency in the supply of another element. Plant analysis may be helpful as an index to such a deficiency. Alto-

gether, plant analysis promises to be a useful tool of investigation. Whether it will be more generally useful cannot be said until there has been further study; and this is by its nature slow and laborious.

Soil and plants are much too complex for any easy or quick way of determining the best methods of soil treatment, apart from exceptional cases. Knowledge that will help farmers with their problems must be gained by continued investigation of basic relations that enter into soil problems; by carefully controlled pot experiments and local field tests, with special chemical studies when necessary; and by further practical observation and experience. Many studies of soils and fertilizers are now under way at this experiment station.

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**Where to Go for Help with Fertilizer Problems.** Your county farm advisor knows local crops and conditions, and can often help with problems of fertilizers and soils. Or he can suggest how to go about getting help from the Experiment Station.

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A farmer's problems will not wait until knowledge about plant nutrition is more complete. How then can he best solve them?

Just what steps a farmer should take can only be decided upon when local conditions are considered. None of the statements in this circular should be taken as a specific recommendation for any kind of treatment in a given situation.

The farm advisor in a county is familiar with local experience and can

often help a farmer adapt his fertilizer practice to his own crop, soil, and climatic conditions. The Agricultural Experiment Station of the University of California is often able to help in solving special soil problems, especially when these are of general interest in the state. A farmer who needs such help should consult the farm advisor in the county where his property is located; or write to the Agricultural Extension Division, University of California, Berkeley.