A study of the fertilization of rice

John Fielding Reed

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By

J. FIELDING REED and M. B. STURGIS
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A Study Of The Fertilization Of Rice

By

J. FIELDING REED and M. B. STURGIS

The coastal prairie section of Louisiana produces more than forty per cent of the rice grown in the United States and represents the largest acreage of rice in one area in this country. The cultivation of rice is of particular importance in this area because it can be grown more profitably than any other crop on these lowlands. The intensive cultivation and the long combined practice of flooding have brought about notable changes in the soil. One of these changes has been the development of deflocculation accompanied by an increase in stickiness, compactness, and impermeability of the soil. In addition, the continuous cropping and flooding have depleted the nitrogen and the phosphorus contents of the soil. Efforts to restore to the soil its former degree of fertility by the use of commercial fertilizers and organic matter in the form of leguminous crops have not been generally successful.

This bulletin reports the results of preliminary laboratory and greenhouse studies of rice fertilization. The investigation has involved determining the effects on the growth of rice of fertilizers from varying sources and the effects of organic matter in the form of ground soybean plants, used singly and in combination with commercial fertilizers. In hope of throwing more light on the fertility problems, the study was supplemented with an investigation of the availability of nitrogen and phosphorus during the growing period of the rice.

REVIEW OF LITERATURE

The literature regarding the fertilization of rice is extensive and scattered. Much of the information is controversial, and much is isolated and rather hard to obtain. The results from the use of commercial fertilizers on rice are often contradictory to results on the upland crops.

Nutrient and Culture Solutions

In order to determine the fertility requirements of rice, a number of studies have been made, involving nutrient and culture solutions and in some cases analyses of the plants. In Hawaii, in a series of plant experiments, Kelley and Thompson (33)* studied the composition of the rice plant at its various stages of growth in the hope that this might throw some light on the questions of how a given fertilizer acts and during what periods the various elements are absorbed. It was found that by the time it is two-thirds grown, the rice plant has normally taken up about four-fifths of its maximum nitrogen and phosphoric acid and nine-tenths of its potash; therefore, fertilizers should be applied before planting or at an early period of development. In common with other cereals, rice demanded an abundance of readily available plant food during early growth.

The assimilation of nutrients by the rice plant was studied by Sahasrabuddhe (55) in Bombay. The analyses of the rice plant showed that it continued the assimilation of its constituents up to the full ripening period and

* Numbers in parentheses () refer to "Literature Cited," page 20.
did not stop when the flowering period began. When the plant came to flowering its powers of assimilation were increased, and maximum assimilation occurred at the "milk" stage.

Carbery (2), in Bengal, reported that the percentages of nitrogen and potassium in the roots, leaves and stems of paddy plants grown in water culture decreased rapidly from the transplantation to the preflowering stage and then remained practically constant. Shortages in potassium and phosphorus supplies were reflected in the composition of the plants but not of the seeds. In the absence of sufficient supplies of nitrogen and potassium the plants were often very high in silica.

Chemical analyses reported by Kapp (29) (31) indicated that the addition of nitrogen to the rice soils in Arkansas resulted in the removal of a larger amount of nitrogen by the plants, which was proportional to the growth and to the straw and grain produced. On the other hand, phosphorus, potassium, and calcium, and possibly iron and manganese in most cases, were removed from the untreated soil in quantities large enough to satisfy the requirements of the rice plant without the necessity of an added application. Kapp reasoned from this that under submerged conditions, the soils contained a sufficient reserve of these elements for maximum growth, provided there was available an adequate supply of nitrogen. Further studies indicated that although the nutrient solution producing the largest grain yield also produced the plants that assimilated the most nitrogen, the percentage of total nitrogen in these plants was not the highest. This suggested that a high percentage of nitrogen in the plants would not, in all cases, be associated with a large yield of rice.

A large amount of experimental work on rice growth and assimilation from various nutrient solutions was conducted by Gile and Carrero. Their studies were concerned chiefly with iron availability and assimilation. Earlier work seemed to show that rice should not assimilate colloidal iron, and that the toxicity of ferric chloride to the plant roots was accompanied by penetration of iron into the roots and transportation to the leaves. Continuing their work, Gile and Carrero (13) (14) (15) grew rice in acid, neutral, and alkaline solutions with different forms and quantities of iron. It was evident that rice was not particularly sensitive to the reaction of the solution except as the reaction influenced the availability of iron. Lime-induced chlorosis was caused by a lack of iron, and it was strongly indicated that the only action of calcium carbonate in inducing chlorosis lay in diminishing the availability of the iron. The amount of available iron in the different solutions could not be determined analytically because of the impossibility of distinguishing between colloidal and soluble iron. Calculations showed, however, that in many cases the concentration of available iron must have been less than one part in ten million parts of solution.

Rice was grown in culture solutions by Gines (16), and the relative effect of different iron salts upon the growth and development of young rice plants was studied. Each salt used was beneficial over certain ranges, and judged by the weight of the plants produced, ferric phosphate was most efficient. When the iron salts were added in 0.0005 molar concentration to rice grown in tap water, all proved deleterious except the ferric phosphate.

The plant-food requirements of rice were investigated by Gericke (12) by growing rice plants for varying periods of time in a complete nutrient
solution and subsequently growing them to maturity in solutions devoid of some of the essential elements. It appeared from this study that very important factors to be considered in the compounding of nutrient solutions for growth of rice are those that affect the absorption and utilization by the plant of the elements potassium, nitrogen, and iron. Iron appeared to be the most important of the elements essential for the growth of rice. Gericke concluded that rice had a low absorptive capacity for iron; the large amounts of iron noted on the roots of certain plants evidenced the fact that it did not enter the rice plant readily. The apparent great need of the rice plant for nitrogen and potassium, both as to quantity received and as to length of time they need to be available, indicated the importance of these elements and reduced the factors that markedly affected the growth of rice in nutrient solutions to the conditions that control the availability of iron, nitrogen, and potassium.

Kimura (36) (37) studied the reaction of rice to mineral nutrients in solution culture. High concentrations of phosphorus were injurious to rice, but this effect was decreased somewhat by increasing the concentration of iron. An undisturbed growth of barley was noticed in a solution containing high phosphorus that was injurious to rice. This was probably due to a higher capacity of barley to absorb iron, or of rice to absorb phosphorus followed by precipitation by phosphorus of soluble iron in the tissues; possibly calcium acts in the same way by reducing the solubility of iron.

A great deal of solution culture work has been done to determine the proper form of nitrogen for rice. In earlier literature the opinion was varied, but the general consensus was that ammonium salts were more effective sources of nitrogen for rice than were nitrates. Kelley (34) attributed the unfavorable action of nitrates in paddy soils in Hawaii to the loss of nitrogen by denitrification, the formation of poisonous nitrites, and loss of nitrates through leaching. Results from his sand cultures showed that if rice had access to nitrates as the only source of combined nitrogen, unhealthy and stunted growth followed, while, on the other hand, ammonium salts brought about vigorous growth and, in every way, normal-appearing plants. In practice the use of ammonium salts or organic nitrogen and not nitrates was recommended for rice culture.

Work carried on elsewhere by Willis and Carrero (67), Hartenbower (17), Bartholomew (1), Gericke (12), and others has indicated that rice plants can utilize applied nitrate compounds. Salinas (56) compared the effects upon young rice plants of different nitrate salts in complete culture solutions. Nitrates of sodium, ammonium, potassium, calcium, and magnesium were beneficial in complete culture solutions, while nitrates of cobalt, copper, and nickel killed rice plants. All ammonium salts that were tried were beneficial to rice. Sodium nitrite as the only source of nitrogen in a complete culture produced fairly well-developed young rice plants. In India, Dastur and others (7) (8) found that the use of a mixture of ammonium salts and nitrates had a more beneficial effect on the growth and gave a greater production of grain.

The absorption and utilization of nitrogen by the rice plant grown in nutrient solution has been studied rather intensively in Arkansas. Early results (25) (26) indicated that the rice plant could develop to maturity when grown on a nutrient solution containing either the nitrate or the ammonium
form of nitrogen. A greater root development was obtained by plants grown in culture solution containing nitrogen in the form of calcium nitrate, and the yields were as great as and sometimes greater than the ammonia-treated plants. Later work (27) (60) with solution cultures indicated that the nitrate nitrogen increased the yield of grain and the weight of the roots. Although ammonia-nitrogen produced about twenty-five per cent more dry matter than nitrate nitrogen, indications were that high concentrations of ammonia nitrogen produced a greater number of sterile heads. The more recent work at Arkansas (31) (32) with nutrient solutions seems to show that the form of nitrogen is not as important as the control of the concentration of hydrogen ions and other elements. In other words, rice plants can be produced in either nitrate or ammonium nitrogen solutions with similar results, provided certain conditions are not varied greatly.

**Fertilization Practices**

Nutrient solution and culture work is rather painstaking and the results are not always applicable to field conditions. Probably the greatest amount of literature on rice soils has had to do with experimental work on their fertilization and management in the field. Practices differ widely, the soils are inherently different, varieties are unlike in their reactions, and the results are therefore somewhat contradictory. The fertilization practices in most of the rice producing areas of the world are reviewed briefly by Copeland in his monograph on rice (6). In Spain, one of the features of rice culture to be highly developed has been the use of fertilizers. The Spanish are most adept in the choice and manner of application of fertilizers. They use ammonium sulphate with particular success in quantities that have been found injurious instead of merely unprofitable in some lands.

Italy has always been the principal seat of the European rice growing industry. The Vercelli experiment station has laid emphasis on the great need for rotation practices to improve the physico-chemical conditions of the soil and thereby insure their future fertility. The value of the use of fertilizers has been generally recognized in Italy. Phosphate has been particularly efficient, while nitrogen has been more effectively furnished by means of legumes. Although potash fertilizers have not been so extensively applied, the Vercelli rice station has established the value of their use for the improvement of the grain, which gains a greater weight, a finer appearance, and a better commercial quality (46).

In Italy, an extensive study has also been made of the most effective times of application of fertilizers. Phosphates are usually applied before working the ground. When a crop to be plowed under has been sown, the phosphorus is applied in autumn in order to aid directly the crop in question. Potassic fertilizers, likewise, are ordinarily applied before the cultivation of the field. The time of application of nitrogenous fertilizers has been a subject of controversy due to their stimulating effect upon weed growth. The most successful use of ammonium sulphate has been through its application in two portions, one before seeding and the other after weeding.

In most parts of the Philippines some improvement can be effected easily by the use of manure, ashes, and decayed matter put in the paddies. Experimental work in the Philippines on the relation of the growth of rice to proportions of the elements in the fertilizers (63) (64) (65) (40) (11) indicated that a high proportion of nitrogen produced the largest yield. The
ratio of N, P, and K varied according to the nitrogen salt used. The best results usually were obtained when ammonium sulphate was the source of nitrogen.

In Indo-China the government has demonstrated the value of fertilizers and has stimulated their use. Cheap domestic phosphate deposits, rather recently discovered, are widely used and regarded as an appreciable factor in yield increases (6).

The practices of rice cultivation in the Indian Empire are many and varied. In upper Burma only cattle manure is used, green manuring being impossible due to the heavy clayey type of soil and the sudden approach of the monsoon. In lower Burma cropping has been continuous, there have been no rotations, and the natives have complained of the declining yields. These conditions have made necessary a transition from intensive to extensive methods of cultivation. The use of commercial fertilizers in lower Burma has increased the yields of paddy in some instances, but has had little or no effect in others (18) (19) (66). In other parts of India the value of green manuring has been definitely established (57). In experimental work, when phosphatic fertilizer was added to the green manure, the growth of the latter was considerably improved, and the effect on the ensuing rice crop was marked (61).

The outstanding feature of Chinese rice culture is the use of natural fertilizers. All waste of man and beast, from city and country, and all garbage are collected, stored without waste, and fermented to the liquid state. This is then applied in the liquid state to the seed beds and to the field as a whole. Even the sluggish streams and canals are dredged and the ooze carried to the field. Only this incessant and meticulous care has made it possible to grow rice "forever" without interruption.

The Japanese follow the Chinese precepts in the use of fertilizers, adding to these practices, however, the scientifically guided use of green manures. The most favored of these are soybeans and genge (Astragalus sinensis), the latter constituting about 71 per cent of all green manures used. Excessive use of genge has been found to be injurious in some cases, due, possibly, to the formation of organic acids and their salts or to the evolution of reducing gases (48) (49) (50). At the Imperial College of Agriculture at Tokyo, Japan, a large amount of scientifically conducted experimental work on elements best suited for fertilizers has been carried on. Complete fertilizers were found to produce greatest crops and phosphate to be the most generally needed element (21). Okado suggests that the application of phosphorus increased the absorption of nitrogen by rice and hastened maturity (47). In addition to having used successfully both ammonium and nitrate forms of nitrogen, Japanese investigators have found that urea, urea-nitrate, and urea-gypsum were suitable sources of nitrogen for rice (62). Commercial cyanamide also gave good results (41).

Investigations carried on by Krauss (38) (39) and Kelley (34) (35) in Hawaii resulted in the recommendation that only nitrogenous fertilizers be used for Hawaiian rice soils. It was found that the application of 150 pounds per acre of ammonium sulphate produced notable increases in yields, but 300 pounds per acre proved the more profitable. Potash and phosphoric acid were without effect. For immediate effects a given amount of nitrogen in the form of ammonium sulphate produced greater returns than nitrogen.
from organic sources, but for a more permanent improvement a rotation of crops, including the plowing under of a legume, was recommended.

Although the growing of rice is relatively recent in the United States, quite a bit of investigational work has been done on management and fertilization. In the Sacramento Valley in California experiments have been conducted at the Biggs Rice Field Station. Earlier work suggested that 150 pounds per acre of ammonium sulphate was profitable, and an occasional year or two of fallow was recommended for improving soil conditions and for weed control (3) (9) (10). Jones, in summing up earlier fertilizer experiments in California, states that manure, sulphate of ammonia, and dried blood increased the yields of rice to a marked extent (22). The application of non-nitrogenous fertilizers failed to increase yields materially. Manure gave the greatest increase and the greatest net profit but was difficult to apply and tended to introduce many weed seeds. Sulphate of ammonia was the easiest to obtain and to apply. A good growth of bur clover turned under in the spring materially increased the yield of rice. The difficulty, however, lay in getting a good stand and growth of bur clover on the old rice land which was poorly drained (23). Later studies by Jones in California confirmed earlier fertility trials (24) only to a certain extent. Bur clover treatments increased the average grain yields significantly. Increases from ammonium sulphate were not particularly satisfactory, but the average grain yields from a combination of ammonium sulphate and superphosphate, or from a complete fertilizer, were considerably higher than the yields from the check plats.

At the Rice Branch Station in Arkansas, considerable work on the fertilization of rice has been done in recent years. In preliminary reports by Nelson (42) (43) (44) on treatments involving numerous combinations of the usual plant food elements, it was noted that in most cases fertilization decreased the yields. The growth of weeds and grasses was stimulated excessively by the fertilizers, to the great detriment of the rice crop. Applying fertilizer after seeding the rice appeared to be a way to avoid the weed difficulty in some instances, though yield increases were scarcely sufficient to be satisfactory. Rotations with cultivated soybeans were effective in cleaning up the land and resulted in increased yields. The use of such cover crops as clover, peas, and vetch was effective in maintaining the level of production when good stands of the cover crops were established in the fall and plowed under early in the spring (60). In later work by Kapp (29) (30), it was reported that large applications of nitrogen every two weeks in the form of sodium nitrate and ammonium sulphate greatly increased the yields of rice. The sodium nitrate, in the most frequent applications, was superior to ammonium sulphate in producing grain. Phosphate and potash applied in large quantities still failed to increase the yields to any extent. The addition of several elements considered as minor was also unsuccessful in increasing yields (30). Recognizing that the application of fertilizers previous to the date of seeding rice had not proven satisfactory, Nelson (45) sought other effective methods. Fertilizers were applied at intervals beginning four weeks before planting and continuing to ten weeks after planting. The greatest increases were from applications made four weeks after planting, increases from later applications being slightly lower. In a study of the use of different materials in rice fertilization, the application, after planting, of a complete fertilizer, made up by adding sulphate of potash to Ammophos,
returned the unusual increase of twenty-five bushels per acre. Heavy applica-
tions of lime reduced the yields. Other studies were made of the possi-
bilities of fertilizing a preceding crop at a heavy rate and thereby increasing
the yield of rice the following season. The economic feasibility of this plan
depended, of course, on applying the fertilizer directly to a crop that would
respond well to fertilizer and have considerable commercial value, thereby
supplementing the increased returns from the rice crop. There was a defini-
tie increase in yield from this experiment. The results from direct and in-
direct application of manure were in distinct contrast; direct application to
rice reduced the yield; application to a crop preceding rice increased the rice
yield the following season.

The most recent results from Arkansas indicate that the growth of rice can
be greatly increased on non-acid rice soil by additions of nitrogenous fer-
tilizers plus acid treatments (32). With treatment of sulphuric acid alone,
the rice soil gave an increase in yield of 230 per cent. A 200-pound appli-
cation of ammonium sulphate gave an increase of 50 per cent, and 800
pounds of ammonium sulphate an increase of 100 per cent. However, the
acid supplemented by 800 pounds of ammonium sulphate increased the yield
400 per cent.

The soils of the Gulf coastal prairie, on which most of the rice of the
United States is grown, extend west of Louisiana into Texas. The results
of fertilizer experiments at the Rice Substation in Texas have been summed
up by Reynolds and Wyche (54). The soils responded to nitrogen and phos-
phorus, nitrogen being needed more than phosphorus. During thirteen years
of experimentation, the largest average yield and most profitable return
resulted from the application of 100 pounds of sulphate of ammonia per acre.
Increases from superphosphate were smaller and combinations of super-
phosphate and ammonium sulphate did not produce larger yields than am-
monium sulphate alone. Potash, when used alone, did not increase the yield
of rice, but did produce significant yield increases when used with super-
phosphate or with superphosphate and ammonium sulphate. During five years
of experimentation, the second largest profit was made from a combination
of 300 pounds of superphosphate and 100 pounds of potassium sulphate. In
work on the time of application of fertilizers, application after planting
brought about larger yields, but in the case of ammonium sulphate this in-
crease was not large enough to justify the trouble and expense involved in
applying the fertilizers at a separate operation. In the case of superphos-
phate, however, the increases resulting from applications six weeks after
planting were significant and profitable and indicate that this method should
be practiced.

Later reports from the Texas Rice Station (68) gave data confirming
the results of preceding years on the station plats. In two cooperative tests
conducted elsewhere by the station, results were somewhat variant. In one
case, where the soil had been cropped to rice every other year for some time,
ammonium sulphate was most beneficial, as in the case of the station plats.
In the other, where the soil had been devoted to rice for only a few years,
response to superphosphate was marked, while response to ammonium sul-
phate was insignificant. Evidently land that has been cropped to rice for
many years is first in need of nitrogen, while newer land responds more
readily to phosphorus.
The largest yields at the Texas station were obtained from rotations. Sesbania and summer fallow rotations were best, followed by cotton and soybeans. In all cases an increase of 100 per cent or more was recorded on plats using a rotation instead of continuous cropping to rice.

Experiments with fertilizers on rice have been conducted at the Rice Experiment Station at Crowley, Louisiana, since 1910 on Crowley silty clay loam, which is the most widely occurring soil of the southwestern Louisiana rice-growing area. As early as 1901 many of the most progressive farmers were convinced that the use of fertilizers on rice was profitable and at that time were drilling 70 pounds per acre of phosphate and potash fertilizers with the seed. This mixture was thought to exert its influence on the crop during the first few weeks of growth (58). In an early paper Zerban (69) considered that the need for potash and phosphate fertilizers on rice was well established and cited a number of cases where they were profitable in short-time trials conducted by rice planters. The advisability of using commercial nitrogen was questioned and the substitution of a legume rotation was suggested. In earlier investigations at the Louisiana Rice Station, Quereau (51) reported best results from 16 per cent acid phosphate at the rate of 200 pounds per acre. Some increases were obtained from the application of nitrogen, particularly on run-down land. Because of trouble with grass and weeds, however, it was not profitable to grow rice longer than five years in succession, even with the use of fertilizers. Quereau concluded from rotation experiments that long-time rotation practices were best and advised clean cultivation of highland crops for six years and then cultivation in rice for six years with fertilization. Short time rotations necessitated the rebuilding of levees and involved too much overhead.

Further studies at the Louisiana Station (4) seemed to show that commercial fertilizers would not increase the yields to a profitable extent. Acid phosphate invariably increased the weed growth. Commercial forms of nitrogen were not helpful when applied alone. Increases in yields from potash applications were insignificant. Horse manure was more beneficial than any kind of fertilizer, but it is scarce on the rice farms. The best yields of rice were obtained not by fertilizing, but by growing the crop in rotation with soybeans. In all earlier reports from the Rice Experiment Station, it was shown that a rotation with soybeans gave a marked yield increase, good weed control, and decided improvement in the physical condition of the soil (5). In the more recent reports (52) (53), the results from the use of any forms of commercial fertilizer were still doubtful. Short time rotation experiments were still proving somewhat beneficial, but not to the desired extent. Rotations with summer fallow were proving almost as successful in maintaining yields as rotations with soybeans and were much less expensive.

Controlled experiments in Louisiana by Sturgis (53) (59), using soil in pot cultures, indicated that the yield of rice might be materially increased by the addition of leguminous organic matter in the form of soybeans. The use of commercial fertilizers without the addition of organic matter was much less effective.

**EXPERIMENTAL PROCEDURE**

In the investigations herein reported the A horizon of a relatively unproductive Crowley silty clay loam was used. This soil was taken from the Rice Experiment Station at Crowley, Louisiana, and had been continually
flooded and used for rice cultivation over a period of forty years. This soil was broken up to pass a one-fourth inch screen. Nine-kilogram portions were placed in three-gallon pots and various treatments were applied, including commercial fertilizers of varying sources and compositions, organic matter in the form of chopped soybean plants, and combinations of commercial fertilizers and organic matter. Rice was planted in these pots, flooded with distilled water three weeks after emergence, and kept flooded until mature. The pots were kept under controlled conditions in the field under a bird and rodent proof fence and exposed to normal rain and sunshine. Distilled water was used as a supplement to rain in order to keep three inches or more of water on the soil. These investigations were carried on for four years, the treatments being varied from year to year. The rice was planted during the usual spring planting period and harvested in the fall. Yields were arrived at from the air-dry weights of straw and grain. During the first three years of the experiment the treatments were mixed with all of the soil in the pots. The rice was germinated in pure sand and transplanted to the pots when three inches high. The Blue Rose variety was used. During the last year of the experiment the procedure was modified somewhat. Four-gallon pots were substituted for the three-gallon size and 11-kilogram portions of soil were used. The fertilizers were applied in a localized area, being mixed with only the upper four inches of soil. The Fortuna variety of rice was used, and it was seeded directly in the pots instead of being transplanted.

To supplement this fertility study, chemical estimations of the availability of nitrogen and phosphorus were made. The soil in the pots was sampled by means of a sampling tube one week after planting, one day after flooding, one week after flooding, and after cutting the rice. The following determinations were made on these samples:

- Phosphorus, 0.05 N hydrochloric acid soluble phosphorus, using a ratio of 1 part soil to 15 parts acid, agitating for thirty minutes, filtering, and determining phosphorus colorimetrically by the molybdate method.
- Nitrate-Nitrogen, using a ratio of 1 part soil to 5 parts water and determining nitrate colorimetrically as recommended by the A. O. A. C.
- Nitrite-Nitrogen, using a ratio of 1 part soil to 1 part water and testing for nitrite by the conventional colorimetric method as recommended by the A. O. A. C.
- Ammonia-Nitrogen, extracted with 0.05 N hydrochloric acid using a ratio of 1 part soil to 15 parts acid, NaOH added, and the ammonia distilled over into standard acid and titrated.

**EXPERIMENTAL RESULTS AND DISCUSSION**

The results of the first two years of fertilizer experimentation (1933 and 1934) have been reported by Sturgis (59) and have guided the choice of treatments for the past two years. The treatments, with resulting yields obtained in 1935 from rice grown in pots, are summarized in Table 1. The most outstanding increases in growth and yield were on the soils treated with leguminous organic matter in the form of chopped soybean plants. When a complete fertilizer accompanied this organic matter treatment, yields were even higher. Increases in head yield of from 140 to 160 per cent resulted from a treatment of organic matter plus 400 pounds per acre of an 8-8-8...
mixture, as compared with 108 per cent increase from organic matter alone. Nitrogen used alone in the form of ammonium sulphate gave a slight decrease in yield, and that in the form of urea did not increase the yields significantly. The combinations of nitrogen and phosphorus, however, increased the yields from 28 to 43 per cent. In all instances the addition of KCl with these two elements was helpful, but in one case its value was questionable. Of the various sources of phosphorus tried, bone meal was particularly promising in a complete fertilizer. There seemed to be little choice between Ammophos (11-48-0) and regular superphosphate.

Table 1. Summary of Rice Fertility Tests, 1935

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<th>No.</th>
<th>TREATMENT</th>
<th>Average head yield, grams</th>
<th>Average straw yield, grams</th>
<th>Increase head yield, per cent</th>
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<td>2</td>
<td>0.5% organic matter (as soybeans)</td>
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<td>21.5</td>
<td>108</td>
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<td>-19</td>
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<td>9.3</td>
<td>-25</td>
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<tr>
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<td>200# 8-0-0 (urea)</td>
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<td>11.2</td>
<td>0</td>
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<td>6</td>
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<td>9.0</td>
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<tr>
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<td>90</td>
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<td>5.8</td>
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<td>7.0</td>
<td>11.2</td>
<td>49</td>
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<td>11</td>
<td>400# 8-8-8 (area-ammophos-KCl) 0.5% O. M. (soybeans)</td>
<td>11.3</td>
<td>30.3</td>
<td>140</td>
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<td>400# 8-8-8 (area-ammophos-KCl) (soybeans)</td>
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<td>15.5</td>
<td>49</td>
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<td>13</td>
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<td>49</td>
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<td>400# 8-8-8 (ammosulf-superphos-KCl)</td>
<td>7.7</td>
<td>15.5</td>
<td>64</td>
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<tr>
<td>15</td>
<td>400# 8-8-8 (ammosulf-superphos-KCl) 0.5% O. M. (soybeans)</td>
<td>12.2</td>
<td>25.5</td>
<td>160</td>
</tr>
<tr>
<td>16</td>
<td>Check, no treatment (soybeans)</td>
<td>4.65</td>
<td>9.0</td>
<td>0.0</td>
</tr>
<tr>
<td>20</td>
<td>Check, no treatment</td>
<td>4.4</td>
<td>8.0</td>
<td>0.0</td>
</tr>
<tr>
<td>21</td>
<td>400# 8-8-8 (ammosulf-fine bonemeal-KCl)</td>
<td>8.8</td>
<td>18.1</td>
<td>100</td>
</tr>
<tr>
<td>22</td>
<td>400# 8-8-8 (medium bonemeal-KCl)</td>
<td>8.75</td>
<td>15.6</td>
<td>99</td>
</tr>
<tr>
<td>23</td>
<td>400# 8-8-8 (coarse bonemeal-KCl)</td>
<td>7.5</td>
<td>16.2</td>
<td>80</td>
</tr>
</tbody>
</table>

In setting up the pot tests for the following year, 1936, the conditions were modified somewhat, as has been mentioned. The Fortuna variety was used, instead of Blue Rose; the rice was planted in the pots instead of being transplanted; four-gallon pots replaced three-gallon pots, with a corresponding increase in the amount of soil; the fertilizer treatments were localized in the surface four inches of the soil, instead of being mixed with the entire contents of the pot. The treatments and the results from these investigations are reported in Table 2, and illustrated in Figures 1 to 4. Part (a) of Table 2 shows the results of the general ratio study, part (b) gives the results of the source of phosphorus study, and part (c) includes a rather specialized study of the effect of particle size of bone meal. The need for
phosphorus can plainly be seen from the general ratio study. Increases in growth and yields were significant from all fertilizers that contained phosphorus, while treatments of 8-0-8 and 8-0-0 were without effect. Both nitrogen and potassium were beneficial, however, in a complete fertilizer. Although these two elements were ineffective singly or in combination without phosphorus, each was of definite value when added in a combination of the other element with phosphorus. The highest increases in yield were obtained with 400 pounds per acre of 8-8-8 and 6-12-6, the increases being 95 and 92 per cent, respectively.

Table 2. Summary of Pot Tests on Rice Fertility, 1936.
(a) General Ratio Study on Crowley Silty Clay Loam

<table>
<thead>
<tr>
<th>Treatment No.</th>
<th>Ratio</th>
<th>Avg. Straw Yield, Grams</th>
<th>Avg. Head Yield, Grams</th>
<th>Per Cent Gain or Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Check, no fert.</td>
<td></td>
<td>13.0</td>
<td>12.55</td>
<td>0.0</td>
</tr>
<tr>
<td>2. 0-8-0</td>
<td></td>
<td>15.9</td>
<td>16.45</td>
<td>+28.0</td>
</tr>
<tr>
<td>3. 0-8-8</td>
<td></td>
<td>18.55</td>
<td>16.60</td>
<td>+28.2</td>
</tr>
<tr>
<td>4. 4-8-6</td>
<td></td>
<td>19.00</td>
<td>21.30</td>
<td>+65.8</td>
</tr>
<tr>
<td>5. 8-8-8</td>
<td></td>
<td>22.10</td>
<td>25.05</td>
<td>+95.0</td>
</tr>
<tr>
<td>6. 0-12-4</td>
<td></td>
<td>21.15</td>
<td>18.30</td>
<td>+42.4</td>
</tr>
<tr>
<td>7. 0-12-0</td>
<td></td>
<td>23.00</td>
<td>19.40</td>
<td>+61.0</td>
</tr>
<tr>
<td>8. 4-12-4</td>
<td></td>
<td>22.30</td>
<td>21.30</td>
<td>+65.0</td>
</tr>
<tr>
<td>9. 4-12-0</td>
<td></td>
<td>21.00</td>
<td>20.25</td>
<td>+57.6</td>
</tr>
<tr>
<td>10. 6-12-0</td>
<td></td>
<td>25.60</td>
<td>19.25</td>
<td>+49.8</td>
</tr>
<tr>
<td>11. 6-12-6</td>
<td></td>
<td>29.70</td>
<td>24.65</td>
<td>+91.9</td>
</tr>
<tr>
<td>12. 8-6-0</td>
<td></td>
<td>29.60</td>
<td>19.40</td>
<td>+51.0</td>
</tr>
<tr>
<td>13. 8-4-0</td>
<td></td>
<td>23.15</td>
<td>21.50</td>
<td>+67.3</td>
</tr>
<tr>
<td>14. 8-4-4</td>
<td></td>
<td>27.60</td>
<td>21.90</td>
<td>+70.4</td>
</tr>
<tr>
<td>15. 8-8-0</td>
<td></td>
<td>32.10</td>
<td>25.05</td>
<td>+51.0</td>
</tr>
<tr>
<td>16. 8-0-8</td>
<td></td>
<td>40.00</td>
<td>28.00</td>
<td>+144.2</td>
</tr>
<tr>
<td>17. 8-8-4</td>
<td></td>
<td>22.85</td>
<td>18.00</td>
<td>+91.2</td>
</tr>
<tr>
<td>18. 4-12-4</td>
<td></td>
<td>22.95</td>
<td>19.35</td>
<td>+105.4</td>
</tr>
<tr>
<td>19. 8-12-0</td>
<td></td>
<td>24.75</td>
<td>17.45</td>
<td>+85.2</td>
</tr>
</tbody>
</table>

1 Ratios based on 400 lbs. per acre. Nitrogen as ammonium sulfate. Phosphorus as superphosphate Potassium as muriate (KCl)

Fertilizers applied—April 20-21, 1936.
Rice planted in pots—April 27, 1936.
Flooded—May 16-17, 1936.
Harvested—September 21, 1936.

Table 2. Summary of Pot Tests on Rice Fertility, 1936 (Continued).
(b) Source of Phosphorus Set-up.

<table>
<thead>
<tr>
<th>Treatment No.</th>
<th>Ratio</th>
<th>Source of Phosphorus</th>
<th>Avg. Straw Yield, Grams</th>
<th>Avg. Head Yield, Grams</th>
<th>Per Cent Gain or Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>17. Check</td>
<td></td>
<td>basic slag</td>
<td>11.75</td>
<td>9.42</td>
<td>0.0</td>
</tr>
<tr>
<td>18. 0-8-0</td>
<td>basic slag</td>
<td>16.50</td>
<td>14.75</td>
<td>+56.6</td>
<td></td>
</tr>
<tr>
<td>19. 1.8-8-0</td>
<td>ammophos</td>
<td>19.30</td>
<td>15.40</td>
<td>+63.5</td>
<td></td>
</tr>
<tr>
<td>20. 2.6-8-0</td>
<td>bone meal</td>
<td>19.40</td>
<td>15.75</td>
<td>+67.2</td>
<td></td>
</tr>
<tr>
<td>21. 8-8-8</td>
<td>basic slag</td>
<td>26.00</td>
<td>21.70</td>
<td>+119.7</td>
<td></td>
</tr>
<tr>
<td>22. 8-8-8</td>
<td>ammophos</td>
<td>31.00</td>
<td>20.35</td>
<td>+116.0</td>
<td></td>
</tr>
<tr>
<td>23. 8-8-8</td>
<td>bone meal</td>
<td>29.00</td>
<td>20.50</td>
<td>+117.6</td>
<td></td>
</tr>
<tr>
<td>24. 6-12-6</td>
<td>basic slag</td>
<td>22.90</td>
<td>18.00</td>
<td>+91.2</td>
<td></td>
</tr>
<tr>
<td>25. 6-12-0</td>
<td>ammophos</td>
<td>31.10</td>
<td>23.00</td>
<td>+144.2</td>
<td></td>
</tr>
<tr>
<td>26. 6-12-6</td>
<td>bone meal</td>
<td>28.85</td>
<td>18.50</td>
<td>+75.2</td>
<td></td>
</tr>
<tr>
<td>27. 6-12-6</td>
<td>bone meal</td>
<td>31.50</td>
<td>17.10</td>
<td>+81.5</td>
<td></td>
</tr>
<tr>
<td>28. 4-12-4</td>
<td>basic slag</td>
<td>23.90</td>
<td>19.35</td>
<td>+105.4</td>
<td></td>
</tr>
<tr>
<td>29. 4-12-4</td>
<td>ammophos</td>
<td>24.75</td>
<td>17.45</td>
<td>+85.2</td>
<td></td>
</tr>
</tbody>
</table>

1 Applied at rate of 400 lbs. per acre. Nitrogen as ammonium sulfate. Phosphorus—Varying. Potassium as KCl.
Figure 1.—Effect of change in ratio on growth of rice: (1) check; (2) 0-8-0; (3) 0-8-8; (4) 4-8-6.

Figure 2. Effect of change in ratio on growth of rice (continued): (5) 8-8-8; (6) 0-12-4; (7) 0-12-6; (8) 4-12-4.
Figure 3.—Effect of change in ratio on growth of rice (continued): (9) 4-12-0; (10) 6-12-0; (11) 6-12-6; (12) 8-0-8.

Figure 4.—Effect of change in ratio on growth of rice (continued): (13) 8-4-8; (14) 8-8-0; (15) 8-8-4; (16) 8-0-0.
Table 2. Summary of Pot Tests on Rice Fertility, 1936 (Continued).

(c) Bone Meal Particle Size Set-up.

<table>
<thead>
<tr>
<th>Treatment No.</th>
<th>Type of Bone Meal</th>
<th>Avg. Straw Yield, Grams</th>
<th>Avg. Head Yield, Grams</th>
<th>Per Cent Gain or Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.</td>
<td>Check, no fertilizer</td>
<td>12.75</td>
<td>13.75</td>
<td>0.0</td>
</tr>
<tr>
<td>31.</td>
<td>Special production 50 X Dust, 3.7% N 22% total phos. acid</td>
<td>20.45</td>
<td>19.20</td>
<td>+39.3</td>
</tr>
<tr>
<td>32.</td>
<td>Regular production, TCC brand 3.7% N 22% total phos. acid</td>
<td>19.90</td>
<td>18.70</td>
<td>+36.0</td>
</tr>
<tr>
<td>33.</td>
<td>Coarse ground soft particles 6.4% N 17.5% total phos. acid</td>
<td>20.35</td>
<td>16.10</td>
<td>+17.1</td>
</tr>
<tr>
<td>34.</td>
<td>Coarse ground hard particles 8.0% N 27.2% total phos. acid</td>
<td>18.10</td>
<td>13.50</td>
<td>-1.8</td>
</tr>
<tr>
<td>35.</td>
<td>Regular superphosphate 20% avail. phos. acid</td>
<td>19.35</td>
<td>17.35</td>
<td>+26.2</td>
</tr>
</tbody>
</table>

These fertilizers were applied at the rate of 150 pounds per acre. No potassium applied and only what nitrogen was present in the bone meal.

In the treatments used to determine the comparative value of different sources of phosphorus (Table 2, part b), yield increases were significant in all cases. Results from superphosphate as a source of phosphorus are not listed in this table, since they were given in the general ratio study (Table 2, part a). The bone meal used was the regular TCC product and the Ammophos was the regular 11-48-0 grade. Previous studies on particle size of Ammophos had indicated that the unscreened product was equally as effective as granulated. The unscreened Ammophos, therefore, was used in these tests. Making up an 0-8-0 mixture with bone meal or Ammophos was of course impossible, so the nitrogen necessarily included is indicated in the ratios for treatments 18 and 19. All sources of phosphorus were so equally effective in all instances that it is not possible to say which would be best. The highest single increase in yield, 144 per cent over that of the check, was observed in a 6-12-6 mixture with Ammophos as the source. In the 8-8-8 and the 0-8-0 ratios, no significant differences in yield resulted from varying the source. Probably the market price per unit would be the deciding factor in a choice of source of phosphorus.

In a special study of the effect of small applications of phosphorus and of the effect of particle size of bone meal (Table 2, part c), applications were made at the rate of 150 pounds of material per acre, regardless of the analysis. Increases of 17 to 39 per cent in yield were realized from all the treatments except coarse-hard bone meal. In this particle-size study of bone meal, the smallest sized particles were most effective, decreasing benefits being observed as particle size increased. The regular-production bone meal gave an increase in head yield of 36 per cent and did not vary enough from that of the dust sized particle to merit special production.

To supplement these fertility tests a chemical study of the availability of nitrogren and phosphorus was made. The details of the experimental methods involved in these analyses have been described under Experimental Procedure. The data from studies of the variation in the chemical form of nitrogen are summed up in Table 3. The four dates of determination that are listed occurred one week after planting, one day after flooding, one week after flooding, and one day after harvesting, respectively. Nitrites were
<table>
<thead>
<tr>
<th>No.</th>
<th>Treatment</th>
<th>Head Yield % Gain or Loss</th>
<th>NITRATE-N, PPM.</th>
<th>NITRITE-N, PPM.</th>
<th>AMMONIA-N, PPM.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Check</td>
<td>0.0</td>
<td>7.0</td>
<td>10.0</td>
<td>2.25</td>
</tr>
<tr>
<td>2</td>
<td>0-8-0</td>
<td>+28.0</td>
<td>7.0</td>
<td>2.50</td>
<td>t</td>
</tr>
<tr>
<td>3</td>
<td>0-8-8</td>
<td>+29.2</td>
<td>16.5</td>
<td>15.0</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>4-8-8</td>
<td>+55.8</td>
<td>25.0</td>
<td>2.5</td>
<td>7.5</td>
</tr>
<tr>
<td>5</td>
<td>8-8-8</td>
<td>+95.0</td>
<td>20.0</td>
<td>25.0</td>
<td>1.25</td>
</tr>
<tr>
<td>6</td>
<td>0-12-4</td>
<td>+42.4</td>
<td>10.0</td>
<td>5.0</td>
<td>t</td>
</tr>
<tr>
<td>7</td>
<td>0-12-6</td>
<td>+51.0</td>
<td>20.0</td>
<td>12.5</td>
<td>t</td>
</tr>
<tr>
<td>8</td>
<td>4-12-4</td>
<td>+65.0</td>
<td>11.0</td>
<td>12.5</td>
<td>3.0</td>
</tr>
<tr>
<td>9</td>
<td>4-12-0</td>
<td>+57.6</td>
<td>10.0</td>
<td>15.0</td>
<td>4.15</td>
</tr>
<tr>
<td>10</td>
<td>6-12-0</td>
<td>+49.8</td>
<td>25.0</td>
<td>20.0</td>
<td>1.0</td>
</tr>
<tr>
<td>11</td>
<td>6-12-6</td>
<td>+91.9</td>
<td>20.0</td>
<td>9.0</td>
<td>t</td>
</tr>
<tr>
<td>12</td>
<td>8-8-0</td>
<td>-3.1</td>
<td>20.0</td>
<td>25.0</td>
<td>1.10</td>
</tr>
<tr>
<td>13</td>
<td>8-4-8</td>
<td>+51.0</td>
<td>16.5</td>
<td>20.0</td>
<td>5.0</td>
</tr>
<tr>
<td>14</td>
<td>8-8-0</td>
<td>+67.3</td>
<td>25.0</td>
<td>16.5</td>
<td>1.0</td>
</tr>
<tr>
<td>15</td>
<td>8-8-4</td>
<td>+70.4</td>
<td>25.0</td>
<td>12.5</td>
<td>2.5</td>
</tr>
<tr>
<td>16</td>
<td>8-0-0</td>
<td>+1.6</td>
<td>16.5</td>
<td>25.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>
never present in any large amount. The quantity was low except for the period one week after flooding, at which time the concentration of nitrites reached two to three parts per million in some cases. All of the treatments, including those in which no nitrogen was used, seemed to increase the amount of nitrate-nitrogen present before flooding. After a week of flooding the nitrites had dropped considerably in both treated and untreated soils and continued to drop steadily, being undetectable when the soils were sampled after harvesting the rice. The content of ammonia-nitrogen likewise showed a rapid decline through the harvesting time, but did not drop quite to the low levels of nitrates or nitrites. After the first week of flooding it is evident that the nitrogen is present only in small amounts in forms that could be considered available.

It is important to note that the ammoniacal nitrogen had been reduced to relatively low values by the end of the growing period.

The readily available phosphorus contents of the soil at these same periods are shown in Table 4. The same rapid decline is noticeable, only small amounts being detectable after cutting the rice. The treatments that included Ammophos and bone meal showed much higher contents of available phosphorus a week after application than did treatments involving basic slag or superphosphate. This higher content persisted in general through the first week of flooding; the bone meal treatments were particularly consistent. Even though the available phosphorus content of the soil at the end of the growing season was low in all cases, it was significantly greater after bone meal treatments.

<table>
<thead>
<tr>
<th>No.</th>
<th>Treatment*</th>
<th>Phosphorus Source</th>
<th>Head Yield Gain or Loss</th>
<th>PHOSPHORUS, P.P.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>%</td>
<td>5-11-36</td>
</tr>
<tr>
<td>17</td>
<td>Check</td>
<td></td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0-8-0</td>
<td>Superphos, 20%</td>
<td>+28.0</td>
<td>4.7</td>
</tr>
<tr>
<td>18</td>
<td>1.8-8-0</td>
<td>Basic Slag, 18%</td>
<td>-56.6</td>
<td>7.5</td>
</tr>
<tr>
<td>19</td>
<td>2.6-8-0</td>
<td>Ammophos, 11-48-0</td>
<td>+63.5</td>
<td>10.4</td>
</tr>
<tr>
<td>20</td>
<td>0-8-0</td>
<td>Bonemeal, regular</td>
<td>+67.2</td>
<td>37.5</td>
</tr>
<tr>
<td>5</td>
<td>8-8-8</td>
<td>Superphos</td>
<td>+95.0</td>
<td>9.5</td>
</tr>
<tr>
<td>21</td>
<td>8-8-8</td>
<td>Basic Slag</td>
<td>+119.7</td>
<td>7.5</td>
</tr>
<tr>
<td>22</td>
<td>8-8-8</td>
<td>Ammophos</td>
<td>+116.0</td>
<td>37.5</td>
</tr>
<tr>
<td>23</td>
<td>8-8-8</td>
<td>Bonemeal</td>
<td>+117.6</td>
<td>37.5</td>
</tr>
<tr>
<td>11</td>
<td>6-12-6</td>
<td>Superphos</td>
<td>+91.9</td>
<td>9.5</td>
</tr>
<tr>
<td>24</td>
<td>6-12-6</td>
<td>Basic Slag</td>
<td>+91.2</td>
<td>9.5</td>
</tr>
<tr>
<td>25</td>
<td>6-12-6</td>
<td>Ammophos</td>
<td>+144.2</td>
<td>12.5</td>
</tr>
<tr>
<td>26</td>
<td>6-12-6</td>
<td>Bonemeal</td>
<td>+75.2</td>
<td>75.0</td>
</tr>
<tr>
<td>27</td>
<td>4-12-4</td>
<td>Basic Slag</td>
<td>+81.5</td>
<td>9.5</td>
</tr>
<tr>
<td>28</td>
<td>4-12-4</td>
<td>Ammophos</td>
<td>+105.4</td>
<td>37.5</td>
</tr>
<tr>
<td>29</td>
<td>4-12-4</td>
<td>Bonemeal</td>
<td>+85.2</td>
<td>75.0</td>
</tr>
<tr>
<td>30</td>
<td>Check</td>
<td></td>
<td>0.0</td>
<td>3.8</td>
</tr>
<tr>
<td>31</td>
<td>150#/A</td>
<td>Bonemeal, 50 X Dust</td>
<td>+39.3</td>
<td>6.4</td>
</tr>
<tr>
<td>32</td>
<td>150#/A</td>
<td>Bonemeal, regular TCC</td>
<td>+36.0</td>
<td>9.5</td>
</tr>
<tr>
<td>33</td>
<td>150#/A</td>
<td>Bonemeal, Coarse Soft</td>
<td>+17.1</td>
<td>6.7</td>
</tr>
<tr>
<td>34</td>
<td>150#/A</td>
<td>Bonemeal, Coarse Hard</td>
<td>-1.8</td>
<td>4.7</td>
</tr>
<tr>
<td>35</td>
<td>150#/A</td>
<td>Superphos, 20%</td>
<td>+26.2</td>
<td>7.5</td>
</tr>
</tbody>
</table>

* Fertilizers applied April 21, 1936, at the rate of 400 pounds per acre unless otherwise specified.

The work on fertilization of rice and improvement of the soils of the rice area is being continued by the Louisiana Agricultural Experiment Sta-
tion. Heretofore the fertility studies have involved only one soil of the rice area, the Crowley silty clay loam. In the investigations started this year, representative soils from all over the rice area are being studied in large cylinders set into the ground at a depth of three feet. The top soil and the sub-soils of each series were placed in these cylinders in a manner approaching as closely as possible their condition in the field. Since at present it is the practice of the farmer to pasture his fallow rice land, the studies of fertilizer application to rice include various rotations with improved pasture both fertilized and unfertilized. In Figure 5 is shown a general view of the pen and cylinders.

In addition to these investigations, a new series of field experiments has been started this year at the Rice Experiment Station at Crowley, Louisiana, under the supervision of Mr. J. M. Jenkins. These tests should furnish more definite information upon which field recommendations can be based.

**SUMMARY**

Rice is grown in Louisiana on the soils of the coastal prairie. Continuous cropping and flooding have degraded these soils and efforts to improve the productivity by the use of commercial fertilizers and organic matter in the form of leguminous cover crops have not been generally successful. This investigation reports the results of preliminary laboratory and greenhouse studies of rice fertilization.

A review of the literature was made. Studies that concern rice fertilization in other parts of the United States and of the world are briefly discussed.
The experimental work involved determining the effect of various fertilizers on the growth of rice in pots. This included the effect of organic matter in the form of soybean hay and of combinations of organic matter and commercial fertilizers. A study was also made of the availability of the nitrogen and phosphorus during the growth period. Results from two years of experimentation are presented. Two years of previous experimentation guided the selection of the treatments used.

Large increases in the growth and yield of rice were obtained from the addition of leguminous organic matter. Commercial fertilizers were not as effective, but substantial increases in yield were obtained from the applications that included phosphorus. Inorganic nitrogen and potassium were ineffective when applied singly or in combination with each other, but were effective when applied with phosphorus. Commercial fertilizers were particularly effective in the latest experiments, in which they were applied in a localized area around the seed.

To supplement the fertility study, determinations were made of the availability of phosphorus and of the various forms of nitrogen in the soil at certain periods during the growing season of the rice. Nitrites were never present in amounts greater than 3 p. p. m. Nitrates dropped rapidly after flooding and were not detectable at the time of harvest. Ammonia-nitrogen also showed a decline, though not as rapid as nitrates. By the end of the growing season all of the forms of available nitrogen were very low.

Available phosphorus showed the same rapid decline except in the treatments in which it was applied in the forms of Ammophos and bone meal. In these cases there was generally present a much greater content of available phosphorus at the end of the growing season.

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