6- to 16-mesh product was not large. Thus, close sizing of the final product appeared to be the most promising solution to the problem of variation in chemical composition of screen fractions.

The presence of coarse raw materials was not advantageous in formulations that granulated readily without nucleation. It was not seriously detrimental in these formulations, but in some cases the granules appeared more nearly homogeneous and more regular in shape when fine raw materials were used.

Acknowledgment

N. L. Spencer and T. L. Holland, Jr., assisted in planning and carrying out the pilot-plant work. Photographs were made by G. L. Crow.

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Received for review October 19, 1957. Accepted February 15, 1958. Division of Fertilizer and Soil Chemistry, 132nd Meeting, ACS, New York, N. Y., September 1957. Part of joint program undertaken in cooperation with U. S. Department of Agriculture.

PHOSPHORUS AVAILABILITY

Effect of Flooding on Plant Availability of Phosphorus from Various Phosphate Rocks

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The phosphate rocks tested under greenhouse conditions on a Cecil sandy loam and a Crosby silt loam fall into three plant-availability groups (60, 30, or 5% as plant available as resin phosphate), whether flooded or unflooded, when applied at the rate of 1 ton per acre. The effect of flooding on the plant availability of phosphate rock varied with the soil and the source of material. The relative plant availability of 10 phosphate sources was measured by four methods: yield of plants, uptake of phosphorus, *A* values, and resin phosphate equivalents. The methods lead to essentially the same groupings of the sources on the basis of phosphorus availability.

UNDER MOST AGRICULTURAL SITUATIONS, the phosphorus of phosphate rock is less readily available to plants than that of superphosphate. Phosphate rocks also vary markedly as to plant availability of the phosphorus when obtained from different sources. Armiger and Fried (*1*), using various sources of phosphate rock on several United States soils, showed marked differences among the sources in their ability to supply phosphorus to buckwheat and alfalfa. The relative magnitudes of the differences among the various sources depended upon the soil to which they were applied. For example, although both a Cecil sandy loam and a Crosby silt loam responded to phosphate application, the differences in the effectiveness of the various rocks as phosphate sources were much greater on the Crosby than on the Cecil soil.

Scattered evidence dealing with submerged soils indicates that phosphate rock may serve as a source of phosphorus for rice. In rice culture, an estimate of the relative effectiveness of various sources of phosphate rock requires agronomic data on flooded rather than on aerated unflooded soils.

This experiment compares various phosphate rocks, under flooded and unflooded conditions, in their ability to supply phosphorus to rice. Two soils from the same series used by Armiger and Fried were used to determine whether the interaction found between soil and phosphate rock applied also when the soil was flooded. The soils were a Cecil sandy loam, a high-phosphate fixing soil, and a Crosby silt loam, a medium-phosphate fixing soil. Seven of the phosphate rocks are the same as those used by Armiger and Fried (*1*).

Experimental Procedure

Colusa, a lowland variety of japonica rice, was grown during the summer in No. 10 cans under greenhouse conditions. When the soil was flooded, about 1 inch of water was maintained on the soil surface; when it was not flooded (unflooded culture), the moisture content was adjusted approximately to field capacity daily. The soils used were a Cecil sandy loam, pH 5.4, from South Carolina, and a Crosby silt loam, pH 5.1, from Indiana. Each pot contained 7 pounds of Cecil soil or 6 pounds of Crosby soil. The treatments, in triplicate, were: 1 ton per acre of each of 10 phosphate rocks (100 to 150 mesh, except for Hyperphosphate, a commercial grade of Tunisian phosphate rock, which was less than 300 mesh) mixed with the entire soil before seeding. A base application of 20 pounds of phosphorus pentoxide per acre in the form of a saturated phosphate resin (IRA 400) tagged with phosphorus-32 was mixed with the soil of all pots (including the check pots). The sources and phosphorus pentoxide contents of the 10 rocks are listed in Table I. The characteristics and surface areas for seven of these materials are given by Caro and Hill (*2*) and Hill, Caro, and Wieczorek (*5*).

Standard phosphorus response curves, flooded and unflooded, were obtained in another series of pots at the same time. The conditions of handling and fertilization were exactly the same except for phosphate application. In this series, saturated phosphate resin (IRA 400) was the only source of phosphorus. The treatments, in triplicate, were: 0, 40, 80, 160, 320, and 640 pounds of phosphorus pentoxide per acre.

All pots were uniformly fertilized with urea, and potassium chloride was applied in solution, just before flooding, in amounts equivalent to 400 pounds each of nitrogen and potassium (K) per acre. An additional 400 pounds of each were added in a single application during the growing season. All fertilizer applications were made on the basis of a 2,000, 000-pound acre.

Twenty seeds were planted in each pot and the seedlings thinned to five when 6 to 8 inches high. The rice was harvested 58 days after seeding (pots were flooded the last 41 days).

Results

The yields of rice tops for both the resin phosphate standards and the various phosphate rocks are shown in Figure 1. There was a marked response to phosphorus on both soils under flooded and unflooded conditions. On the Cecil soil that received the resin phosphate standards (right side of figure), the upland treatment gave higher yields than the flooded treatment at the lower phosphate levels, and lower yields at the higher phosphate levels. On the Crosby soil, the flooded treatment gave a slightly higher yield than the unflooded treatment at the lower phosphate levels and much higher yields at the higher phosphate levels.

Large differences in yield were associated with the various phosphate rocks. On the Cecil soil, flooding increased yield when the yield was above 10 grams of dry matter per pot; on the Crosby soil flooding either had little effect or increased yields. This difference in flooding effect between the two soils with the several phosphate rocks was similar to the results obtained with the resin standards. On the basis of yields, the two best materials were Hyperphosphate and Gafsa Tunis phosphate rock, while the four poorer materials were Idaho phosphate rock, Tennessee brown phosphate rock, India apatite, and Virginia apatite.

The phosphorus uptake data for both the resin standards and the phosphate rocks are given in Figure 2. With the resin standards (right side of figure), the total phosphorus uptake increased with increasing rate of application under both flooded and unflooded conditions. On the Cecil soil, flooding increased the phosphorus uptake at the higher phosphate levels and decreased the uptake at the two lower levels. On the Crosby soil, flooding increased phosphorus uptake slightly at the lower phosphorus levels and markedly at the higher levels. Large differences were associated with the various phosphorus rocks.

On the Cecil soil, flooding gave an increased phosphorus uptake with the three best materials and a decreased uptake with all the others, except the India nodules. On the Crosby soil, the effect of flooding on phosphorus uptake varied with material.

Comparing the phosphorus uptake of the resin standards with those of the phosphate rocks, the 10 rocks may be divided in three groups: Group 1, Hyperphosphate, Gafsa Tunis phosphate rock, and Curaçao phosphate rock; Group 2, South Carolina land rock, India phosphate rock nodules, and Florida land pebble; and Group 3, Idaho phosphate rock, Tennessee brown phosphate rock, India apatite, and Virginia apatite.

As each of the pots in the phosphate rock series received a base application of 20 pounds of phosphorus pentoxide per acre as phosphorus-32–tagged resin phosphate, data were obtained for estimating plant availability of each of the rocks in terms of the resin standards through isotope measurements (*3, 4*). This calculation involves subtracting the *A* value of soil alone from the *A* value of soil plus phosphate rock. The results are shown in Figure 3. The 10 sources are again grouped in the same manner as by the

Table I. Phosphorus Content of Various Phosphate Rocks

Lab. No.	Phosphorus Source	Total P_2O_5 %	Total P_2O_5 Lb./ton of rock
3249	Hyperphosphate[a]	29.5	590
1551	Gafsa Tunis phosphate rock	29.9	598
985	Curaçao phosphate rock	37.9	758
1484	South Carolina land rock	27.1	542
3121	India phosphate rock nodules	25.8	516
910	Florida land pebble	30.9	618
1253	Idaho phosphate rock	33.0	660
907	Tennessee brown phosphate rock	35.0	700
3120	India apatite	29.9	598
1295	Virginia apatite	40.3	806

[a] A commercial grade of Tunisian phosphate rock.

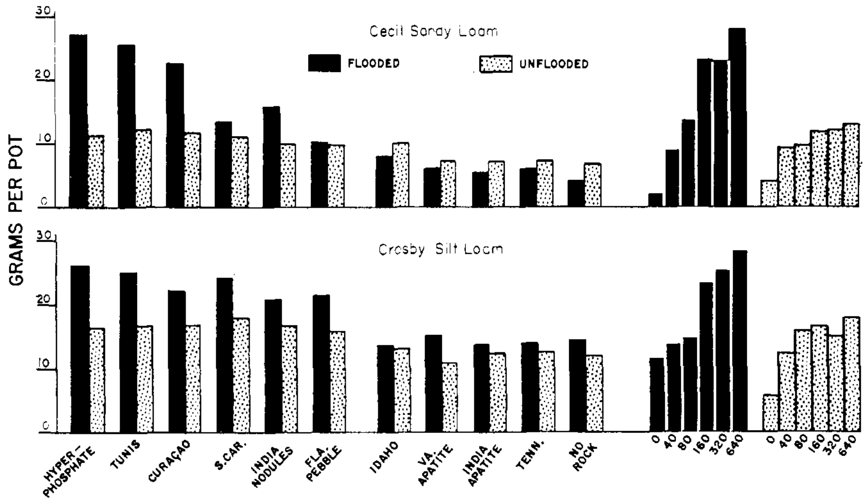

Figure 1. Effect of source of phosphorus, flooding, and soil type on rice yields

Phosphate rock sources, 1 ton per acre plus 20 pounds of phosphorus pentoxide per acre of resin phosphate

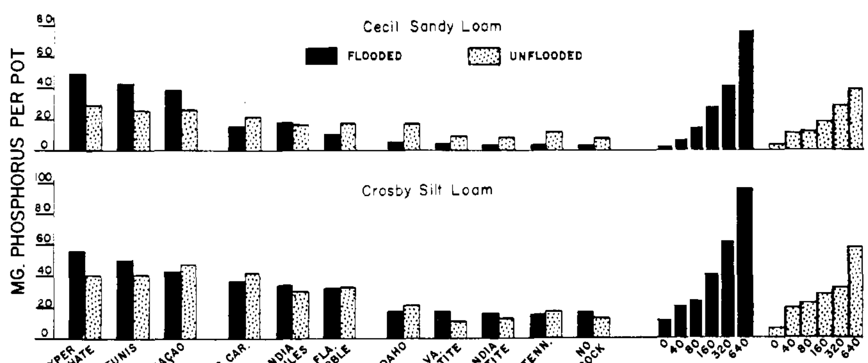

Figure 2. Effect of source of phosphorus, flooding, and soil type on phosphorus uptake of rice

Phosphate rock sources, 1 ton per acre plus 20 pounds of phosphorus pentoxide per acre of resin phosphate phosphorus uptake data. The A value for the Cecil soil was 54 pounds of phosphorus pentoxide per acre when flooded and 32 when unflooded; for the Crosby soil, 123 pounds of phosphorus pentoxide per acre when flooded and 65 when unflooded. The Cecil soil contains less plant available phosphorus than the Crosby soil and flooding increases plant available phosphorus in both soils.

Discussion

The plant available phosphorus of these materials may also be determined graphically from the standard yield-of-phosphorus curves obtained with resin phosphate—i.e., the amount of phosphorus pentoxide from resin phosphate, which provides the same phosphorus uptake as 1 ton of phosphate rock. Separate standard curves were used for flooded and unflooded conditions (Figure 4). The values have been corrected for the base application of 20 pounds of phosphorus pentoxide per acre of resin phosphate applied to all phosphate rock pots. The materials fall in the same groups as obtained by other methods, but absolute values differ (Figures 3 and 4).

The various phosphate rocks provided unequal rates of phosphorus pentoxide application due to variations in their phosphorus pentoxide content. Adjustment of the data (Figures 1, 2, 3, and 4) to correct for these unequal rates—i.e., yield and uptake per unit of applied phosphorus pentoxide—does not cause any material, except for South Carolina land rock, to fall in a different group. However, it does cause slight changes in rankings within groups. The change in the ranking of South Carolina land rock places this material in Group 1, when used on Cecil soil flooded conditions.

The four methods for measuring plant availability lead to essentially the same groupings of the sources on the basis of phosphorus availability. However, the latter three methods are more sensitive measurements and, therefore, allow more differentiation than vegetative yield. Considerable differences have been demonstrated in the relative plant availabilities of these materials. Group 1 is about 60% as available, Group 2 is about 30% as available, and Group 3 is only 5% as plant available as resin phosphate under greenhouse conditions.

The flooding effect upon the plant availability of the 10 phosphate rocks as measured by A values (Figure 3) or resin phosphate equivalents (Figure 4) depended upon the relative availability for the group within which they fell and the soil.

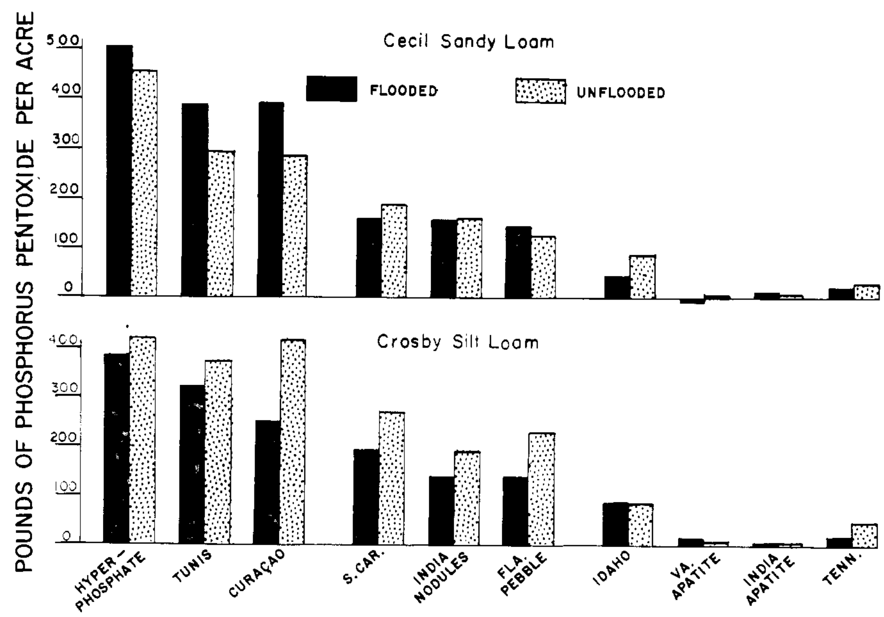

Figure 3. Resin equivalence of various sources of phosphate rock—A value of soil plus rock minus A value of soil alone

Phosphate rock sources, 1 ton per acre

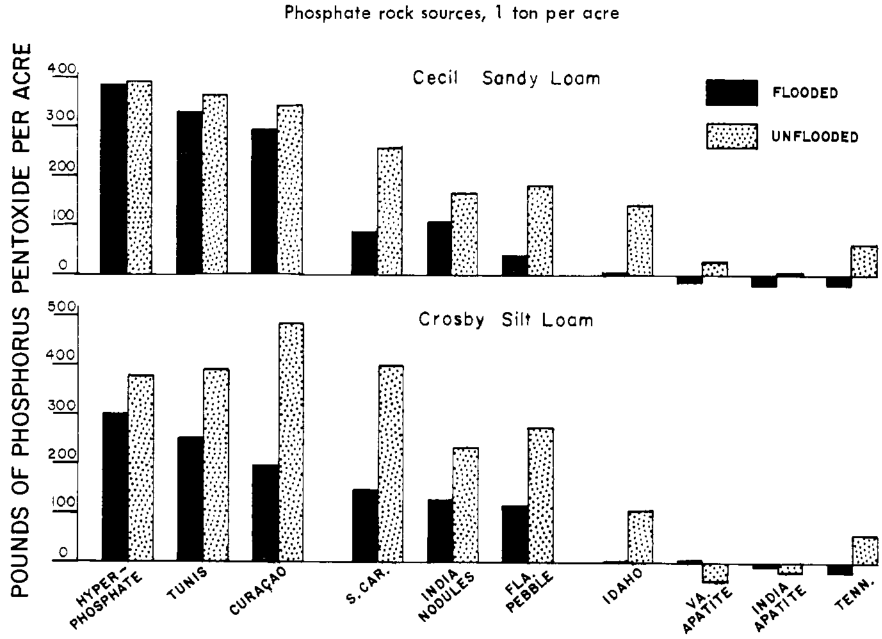

Figure 4. Resin phosphate equivalence of 1 ton of phosphate rock from various sources as measured from yield of phosphorus curves obtained with resin phosphate

Phosphate rock sources, 1 ton per acre

Flooding increased plant available phosphorus in both soils but had a variable effect upon plant availability of the phosphate rocks. Flooding may also increase the capacity for plant growth and phosphorus uptake. This effect is observed only when the general nutrient status of the medium is high, which may explain the more pronounced flooding effects at the higher phosphate levels.

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