

Prediction of the Economically Optimal Phosphorus Fertilizer Needs of Rice *

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ABSTRACT

Trials were conducted with different varieties of rice grown on various types of soils in different parts of Ceylon in cultivators' fields with dressings of phosphorus ranging from 0 to 120 lb. P_2O_5 per acre over basal dressings of nitrogen and potassium and at harvest the grain yields corresponding to the different P_2O_5 applications were recorded. Curves were then fitted to these values using equations of the form $y = a + bx + cx^2$ with c small and negative, different soils giving different values for a , b and c . y represented the yield of grain in bushels per acre and x the quantity of fertilizer P_2O_5 applied per acre. By obtaining regression equations and establishing correlations it was found possible to predict the economically optimal quantity of phosphorus fertilizer to be applied and the yield response to be expected therefrom by determining the soil value for available phosphorus as given by the $NaHCO_3$ method of Olsen.

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INTRODUCTION

UNTIL almost a century ago when world population density was relatively low and the area of cultivable land correspondingly plentiful, the twin problems of depletion of soil fertility and increasing nutrient deficiency were solved by adoption of the system of agriculture known as "shifting cultivation" or "bush fallow". With the population density as high as it is today, it is evident that the required increase in crop production must be procured by other means.

During the last hundred years or so, and more particularly during the last thirty years, science has succeeded in providing improved varieties of seed, better control of plant diseases and insect pests, improved tillage and cultural practices. Notwithstanding these various contributions it is however, probably true to say that the most important single factor in substantially increasing food production during this period was the discovery and adoption of the use of chemical fertilizers.

With the advent of chemical fertilizers for increased agricultural production the necessity for an accurate assessment of soil fertility and nutrient status became imperative and this need gave rise to a new branch of agricultural research whose primary aim was to develop methods of analysing soils for the purpose of predicting the fertilizer requirements of crops.

Together with the advances made in the field of chemical analysis of soils and the study of soil-fertility, there arose various systems of soil classification and soil survey. In Ceylon, the pioneer work in this field was that of Joachim (1955) and his collaborators who in 1935 commenced a systematic investigation of the soils of the island on a pedological basis and produced the first soil map of Ceylon, which is undoubtedly classical and still continues to be widely used on account of its soundness and practical utility. This map was followed by the second soil map of Ceylon by Panabokke (1962).

Soil survey provides information on very broad lines and gives an indication of the fertility status and potential of a soil; this information, however, though useful is not sufficiently precise and detailed to enable decisions to be made regarding the kind and quantity of fertilizer to be used. The knowledge required for the intelligent use of fertilizer could be obtained only through comprehensive and co-ordinated programmes of laboratory, greenhouse and field studies.

The first attempts at assessing the chemical fertility of soils were mainly directed towards the determination of the total amounts of the major nutrients nitrogen, phosphorus and potassium present in the soil. It was, however, realised very early that a relationship between the total amounts of the nutrients in the soil and their availability to crops was unlikely as judged by crop performance. The next logical step, therefore, in the search for a sounder method

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of estimating the fertilizer needs of the growing plant appeared to be to simulated the conditions under which plants obtain their nutrients. Dyer (1894) assuming that "plants help themselves to a part of their mineral food by means of the solvent action of their acid root sap on the particles of soil with which the rootlets come into contact", estimated the acidity of crushed root sap of over a hundred different plants of twenty different natural orders and found the average value in terms of hydrogen to be 0.013 per cent. Out of a number of acids tested for this purpose citric acid appeared to be the best extracting agent and plant acidity in terms of citric acid was found to be 0.91 per cent which was then rounded off to one per cent. Although this method is still sometimes used, it gradually came to be realised that it had its limitations, since different plants have different requirements of nutrients and likewise their ability to extract them from the soil also varied. Thus there came into being various methods of extracting nutrients from the soil including the rapid systems of soil test worked out mainly in America.

With the discovery and adoption of a variety of chemical extractants there arose new concepts such as "capacity factor", "intensity factor" and "rate factor" for defining and determining the availability of plant nutrients in the soil. Doyle and Matsuo (1964) in their excellent paper on the significance of capacity, intensity and rate factor, emphasise the following points: The relative importance of these factors naturally varies with different crops. "Capacity factor" refers to the quantity of nutrient potentially available for mineralization or other forms of release. This depends on the volume of soil that could be explored by the roots. It should, therefore, be particularly significant in the case of those crops with extensive root systems and crops which take up their nutrients gradually over an extended period rather than rapidly in the early stages of their growth. The "intensity factor" refers to the strength of retention or degree of availability or the rate at which it is released. This has a greater significance in relation to highly-responsive rapidly-growing crops with limited rooting systems and those that respond markedly to localised placement of nutrients. In general, the capacity factor should be more applicable to cereals and grasses and the intensity factor to crops such as the potato and other quick growing vegetables. "Rate factor" refers to the transport of nutrients to the roots, replenishment from the reserves and how soon the released nutrient becomes available to the roots. However, although it is true that different factors have different significance for different crops and soils, it also happens to be the case that the capacity and intensity factors are generally highly correlated, and in respect of paddy in its submerged environment the rate factor does not appear to be of much consequence. To sum up these, a satisfactory chemical extractant of soil should be one that gives a composite index of all relevant factors.

The suitability of any method of chemical analysis employed for determining the "availability" of a plant nutrient in soils must ultimately depend to a large extent upon the degree of correlation of soil analytical data and responses of a given crop to application of fertilizer on different soils. Some of the extractants presently in use in different countries for estimating the "available phosphorus" of soils with seemingly satisfactory results are:—one per cent. citric acid (Dyer, 1894), 0.002 N H_2SO_4 buffered to pH 3.0 with ammonium sulphate (Truog, 1930), 10 per cent. solution of sodium acetate in 3 per cent. acetic acid at pH 4.8 (Morgan, 1941), 0.025 N HCl + 0.03 N NH_4F (Bray, 1945), 0.10 N HCl + 0.03 N NH_4F (Bray, 1948), 0.5 M NaHCO_3 at pH 8.5 (Olsen, 1954). Judging from a number of studies which have compared or examined the value and usefulness of several of the methods currently in use (Thompson and Pratt, 1954; Datta and Kamath, 1959; Thamhane and Subbiah, 1960; McConaghy and Stewart, 1963; Chang and Juo, 1963; Nagarajah, 1963, 1964; Doyle and Matsuo, 1964; Chang, 1964), it would appear that the NaHCO_3 extractant method has gained a wide measure of acceptance. These extractant procedures include strong acids, weak acids, buffered solutions, solutions having exchangeable anions, and alkaline solutions.

Phosphorus in the soil is to be found in both the organic and inorganic forms but it is generally true to say that it is the inorganic phosphorus fraction which is usually the more readily available to plants. These inorganic forms could be classified into four chemical forms, namely, aluminium phosphate, iron phosphate, calcium phosphate and occluded phosphate. A suitable soil test should be able to selectively extract a definite proportion of the various forms of phosphate in the same relative amounts in which they are absorbed by plants and thus provide a quantitative measure of the availability of phosphorus. Thus, if iron phosphate is the dominant soil phosphorus fraction available to plants alkaline extractants would appear the most suitable; if on the other hand both calcium and iron phosphate contribute to the availability, an organic acid such as one per cent. citric acid or Bray's acid flouride solutions should suffice. Strong acid solutions seem feasible only on soils containing small amounts of calcium phosphate and are definitely unsuitable for soils predominant in calcium phosphate, as such solutions cannot differentiate between the surface or highly dispersed calcium phosphate which will be available to plants and that part of calcium phosphate in the coarse soil fraction which may be unavailable to plants (Chang, 1964).

Al Abbas and Barber (1964) in their studies on fractionation of soil phosphorus and the uptake of phosphorus by millet, convincingly demonstrated by using the method of multiple correlations and regressions, that the iron phosphate fraction of soils was the dominant source of availability even in soils that contained larger amounts of calcium phosphate than iron phosphate.

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It is a well established agronomic fact that one of the benefits of flooding is the resulting increase in availability of soil phosphorus, whether this be measured by the degree of its concentration in the soil solution, by the magnitude of the A-values, or by the uptake by rice (Fujwara, 1950; Shapiro, 1958a, 1958b; Chang and Chu, 1959; Davide, 1964). Increase in availability is a consequence of hydrolysis and reduction of soil phosphate. The importance of reduction in addition to hydrolysis in releasing soil phosphorus has been emphasised by Fujiwara (1950) and Mitsui (1955). Phosphate in flooded soil seems more mobile than in upland soil; this is possibly due to the greater accumulation of iron phosphate in flooded soil and the greater mobility of iron in the reduced medium. The oxidised ferric phosphate form, which is sparingly soluble, is reduced to the very soluble form of ferrous phosphate in the anaerobic environment. Chang and Chu (1961) demonstrated that applied phosphate changes quicker to iron phosphate in flooded soil than in upland soil. Tyner Davide (1962) established that paddy soils of Japan abound in iron phosphate. Paddy soils of Taiwan with acid parent materials have been found to be abundant in iron phosphate (Chu and Chang, 1960). Tyner and Davide (1962) and Chang and Juo (1963) in evaluating the criteria for selecting a soil phosphorus test for lowland rice stressed the importance of iron phosphate as a source of available phosphorus. The literature cited above points to the fact that the iron phosphate fraction in soils serves as the main source of phosphorus available to rice.

As flooding increases the availability of soil phosphorus mainly by chemical reduction of the sparingly soluble ferric phosphate to the very soluble ferrous phosphate and as applied phosphate fertilizer changes quicker to iron phosphate in flooded soil than in upland soil, it follows as a logical corollary that the form in which phosphate fertilizer is applied is unimportant for flooded rice. Numerous experiments have demonstrated that there have been no significant differences in yield resulting from the use of different forms of phosphate fertilizer except on strongly acid soils where superphosphate may not perform as well as others and in alkaline soils where rock phosphate may prove to be inferior. In Ceylon, experiments conducted throughout the island have shown no significant differences in yield arising from the use of phosphate fertilizers having different chemical compositions (Ponnamperuma, 1958, 1960) and resulting from these experiments, rockphosphate, the least expensive form of phosphate, is now used.

An important aspect of phosphorus nutrition of the rice plant is the luxury consumption of phosphorus as shown by Seneviratne (1965). His solution culture studies indicate that with increasing levels of phosphorus, though the percentage of phosphorus in the plants increases, the weight of plants increases; reaches a maximum, and then declines. From Seneviratne's work it could be inferred that at higher levels of phosphorus there could actually be a decrease in yield of grain and that what is important is not the phosphorus uptake of

the plant but the grain producing efficiency of the absorbed phosphorus. In fact, whether it be the application of phosphorus, nitrogen or potassium, or any other agronomic practice, it is its grain producing efficiency that should be the ultimate criterion of assessment.

Another important aspect is the time of application of phosphorus fertilizer and this would depend both on the requirements of the rice plant and the availability of soil phosphorus. It is established that the rice plant absorbs phosphorus continuously from germination to the flowering stage; during the early stages this absorption is slow, but it rises rapidly from panicle initiation to heading. When soils are flooded, reduction gradually intensifies with the passage of time, and the soluble phosphorus steadily increases; that is, the solubility and availability of soil phosphorus would be small in the early stages of flooding and would progressively increase in the later period of the growth of the rice plant. Thus the rice plant would respond more to a basal application of phosphorus fertilizer. This is the general experience and the common practice and it is a marked contrast to the general recommendation of split applications of nitrogen fertilizer.

Though considerable advances were made during the last century in the field of soil chemistry and the techniques of chemical analysis of soils, and experience was gained in the wide use of soil tests and fertilizer practices, correlation studies on available soil phosphorus, applied fertilizer phosphorus and crop responses are meagre and apparently not conclusive. Bray (1948) following Mitscherlich (1930) used the percentage yield concept— $(\text{No P yield}/\text{P yield}) \times 100$ —and attempted to correlate soil test values with crop responses. Mitscherlich's equation $Y = A - be^{-ax}$ acknowledgedly classical suffers from the limitation that its validity rests on the assumption that the yield curve is asymptotic; whereas it is now known that the yield-fertilizer curve takes a parabolic shape with a maximum value. Even when the soil test values for different soils are the same or nearly the same it has frequently been found that yields can vary greatly as a result of differences in soil productivity due to factors other than the phosphorus status. It was partly as a means of overcoming this seemingly inconvenient situation of dealing with a wide range of absolute yield differences, that the percentage yield concept had been invoked; but even this does not appear to be logically satisfactory since it assumes that the yield response is a function dependent on and proportionate to the absolute yields. Correlation studies on rice have been reviewed by Chang (1964) and it would appear from his study that the NaHCO_3 extractant of Olsen yields the best results over a wide range of pH. In all these studies the underlying principle had been the same, namely two treatments being used, one containing the essential nutrients in amounts that are neither deficient nor in harmful excess, the other being identical with the first except that phosphorus is omitted. Using the percentage yield concept stated above, correlations have

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been calculated between percentage yields and the different soil test values obtained from various soil extractants, and a suitable soil extractant selected. In the survey of the literature on this subject the author noticed the absence of any experiment where a number of incremental rates of phosphorus had been applied and an attempt made to fit mathematical equations to the resulting yield-fertilizer curve and to establish correlations of soil test values with the parameters of these equations with a view to predict the optimum phosphorus requirements.

Based on chemical analytical data, soils are now classified as "low", "medium" or "high" in their phosphorus status; sometimes additional levels such as "very low", "medium low", "medium high" and "very high" are also used. Olsen's (1954) limits for his NaHCO_3 method were less than 20, 20 to 50, and greater than 50 lb. P_2O_5 per acre. The soil specialists, using their knowledge of soils and advances in the theory of Soil Chemistry, experience gained in fertilizer practices, and giving due weight to such factors as economic considerations, subsidies on fertilizers and guaranteed price schemes, make general recommendations, even though studies on calibration of soil test values with applied fertilizer and yield responses have not so far yielded satisfactory results.

An experiment was conducted by the author (Rodrigo, 1962) under greenhouse conditions with nine different paddy soils, where each soil received five levels of phosphorus in the form of saphosphosphate, the treatments being 0, 20, 40, 80 and 120 lb. P_2O_5 per acre. Adequate dressings of nitrogen and potassium were given. The grain yields for each soil increased, reached a maximum and then decreased with the increasing levels of phosphorus added. Graphs drawn with grain yields per pot (y) and the amounts of fertilizer P_2O_5 (x) fitted the second degree polynomial $y = a + bx + cx^2$ with c small and negative. Different soils gave different values for a , b and c . "Available phosphorus" was determined by the NaHCO_3 method of Olsen. The optimum yield was defined as the yield where the gradient (dy/dx) was equivalent to one bushel per acre divided by the amount of fertilizer P_2O_5 , whose cost is twelve rupees (the value equivalent of a bushel of paddy under the government guaranteed price scheme). Graphs were drawn, regression equations obtained and correlations established between the following :—

- (1) The optimum yield responses (optimum yields minus the yields with no phosphorus) and the soil test values for available phosphorus.
- (2) The optimum quantities of fertilizer P_2O_5 to be applied and the soil test values for available phosphorus.
- (3) The optimum yield responses and the optimum quantities of fertilizer P_2O_5 to be applied.

It was deduced that there was a possibility of predicting the quantity of fertilizer phosphorus to be applied and the yield response to be expected by analysing the soil for available phosphorus.

In the present study the results of field tests are reported.

MATERIALS AND METHODS

TRIALS were conducted with rice in cultivators' fields in 30 locations scattered over various parts of Ceylon, representing a wide variety of soils and climates. At each location there were seven plots, which were given seven levels of phosphate in the form of saphosphosphate, the treatments being 0, 20, 40, 60, 80, 100 and 120 lb. P_2O_5 per acre. These treatments were randomly assigned to the plots at each experimental site. Saphosphosphate, the least expensive form of phosphate, was used since it is now known that both availability of soil phosphorus and utilization of applied fertilizer phosphorus are high in submerged paddy soils and furthermore there have been no significant differences in yield resulting from the use of different forms of phosphate fertilizer in experiments conducted throughout the island (Ponnamperuma, 1958, 1960). Dressings of nitrogen and potassium were given to all plots in accordance with the recommendations of the Department of Agriculture for improved varieties for the particular location. At harvest the grain yields were recorded for each treatment.

Special care was exercised in selecting the experimental sites, which were so chosen as to be representative of the ranges in soil type and cultural practices and were also free from the danger of flood damage and drought injury. Care was also taken to see that the sites were large enough to accommodate all plots in a consecutive fashion in the same contour with the longer side of one plot laid adjacent to the longer side of the next plot. Each plot was rectangular in shape and had an area of one hundredth of an acre, the dimensions being 30 ft. $\times$ 14 $\frac{1}{2}$ ft. The plots were bounded by earth bunds 8 inches high and 10 inches broad. In order to eliminate the possibility of soil heterogeneity which might vitiate the treatment effects, as well as to provide for each of the different treatments as nearly as possible similar conditions, sites were selected which were of uniform fertility; this was ensured by making careful inquiries regarding previous crop performance.

The importance of sampling soils cannot be overemphasised when it is realised that a few grams of soil are analysed as being representative of several million kilograms. At each experimental site, therefore, before applying fertilizers, three spadefuls of soils up to a depth of nine inches from different positions in the plot were taken from each plot, thus making a total of twenty one samples. These were then thoroughly mixed and a two-lb. composite

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sample placed in a polythene bag. These polythene bags were then labelled and despatched to the chemical laboratory, where they were air-dried and after being sifted through a 2 mm. sieve were used for chemical analyses.

The NaHCO_3 method of Olsen et al (1954) was used for the extraction of available phosphorus of the soils and the colour development of the extract was done by the method of Dickman and Bray (1940). Rigorous standardisation of every step in this chemical determination was found to be essential in order to get reproducible results. A detailed description of the procedure to be followed is given by Olsen ; after preliminary tests, however, a few modifications were made in the original method. The soil extractant was a 0.5 molar NaHCO_3 solution adjusted to pH 8.5 with 15 per cent. NaOH . As carbon black releases phosphorus when treated with NaHCO_3 , it was pretreated by leaching with NaHCO_3 extractant until the leachate was free from phosphorus, then washed with water and dried in an oven at 40 degrees Centigrade. The molybdate-HCl reagent of Dickman and Bray was modified as proposed by Olsen by adding an extra 50 ml. of 10.0 N HCl per litre. Stannous chloride stock solution was prepared by dissolving 10 grams of $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ in 25 ml. of 10.0 N HCl and the dilute reagent was obtained by diluting with water 1.0 ml. of the stock solution to 127 ml. The standard phosphorus solution contained 5 ppm of P.

The soils were now passed through a one mm. sieve. 2.5 grams of soil plus one teaspoonful of carbon black plus 50.0 ml. of the NaHCO_3 extractant were placed in a 250 ml. conical flask and shaken in an electrically-operated horizontal shaker—"Eberbach Rotator"—for half an hour and filtered through Whatman No. 40 filter paper. For developing the colour the following quantities of reagents were used :—

10.0 ml. of sodium bicarbonate soil extract.

6.5 ml. of distilled water.

5.0 ml. of ammonium molybdate reagent.

2.5 ml. of 1.0 N HCl.

1.0 ml. of stannous chloride reagent.

0 to 2.5 ml., in increments of 0.5 ml., of a 5 ppm P solution were used for the colour development of the standards. To each standard were added 10.0 ml. of NaHCO_3 extractant, 5.0 ml. of ammonium molybdate reagent, 2.5 ml. of 1 N HCl and 1.0 ml. of stannous chloride reagent and made up to 25.0 ml. with distilled water. The transmittancy of the colour was measured by a Coleman's Junior Spectrophotometer after four minutes and before the lapse of ten minutes of the reduction of the heteropoly acid by the addition of stannous chloride. Precautionary measures as given by Olsen were observed in this determination.

RESULTS AND DISCUSSION

RESULTS of the chemical analysis of the soils are given in Table I. Their available phosphorus varied from 13.7 to 70.7 lb. P_2O_5 per acre (1 acre = 2×10^6 lb.), pH from 4.4 to 7.8, nitrogen from 0.04 to 0.78 per cent., organic matter from 0.8 to 26.1 per cent. t.e.b. from 2.4 to 11.8 m.e. per 100 grams, c.e.c. from 6.2 to 26.4 m.e. per 100 grams, and their texture varied from sandy loams to silty clays.

The grain yields at each location increased, reached a maximum and then decreased with the increasing levels of phosphorus applied. The grain yields which were reckoned in bushels per acre (y) and the amounts of fertilizer P_2O_5 applied per acre (x) fitted the second degree polynomial $y = a + bx + cx^2$ with c small and negative; different locations gave different values for the parameters a , b and c . These equations are given in Table 2. The trials in three locations had to be abandoned owing to faulty laying out of the plots and the results from two locations were not considered further as the regressions of these two equations subjected to analysis of variance were found to be non-significant. The yield fertilizer curves were fitted by the method of orthogonal polynomials of Fisher and Yates (1953), and standard statistical procedures were used for all calculations. The results of 25 locations were further studied and are reported on.

The initial yield of a location is taken as the yield in bushels per acre with no P_2O_5 added.

The maximum yield is the yield where the gradient (dy/dx) of the equation $y = a + bx + cx^2$ is equal to 0.

The maximum P_2O_5 to be applied is at the point of maximum yield.

From the yield-fertilizer equations it will be observed that the fertilizer dressing which gives the maximum yield will not give the maximum profit, and hence optimum values are introduced. The optimum yield is defined as the yield where the gradient (dy/dx) is equal to one bushel per acre divided by the amount of fertilizer P_2O_5 the cost of which is equal to the guaranteed price of a bushel of paddy, namely Rs. 12. Or to state this in other words, the optimum yield is at the point where the gradient indicates an increase in yield of one bushel per acre brought about by the addition of that quantity of P_2O_5 whose cost is Rs. 12, i.e., the point beyond which further applications of fertilizer give increases in yield the value of which is less than the cost of the fertilizer required to produce the increase. It therefore follows that beyond this point the application of fertilizer is unremunerative. It will be shown later that the optimum yield gives the maximum profit. Taking the cost of saphosphosphate which contains 27.5 per cent. P_2O_5 to be Rs. 278 per ton, the gradient at the optimum yield was calculated and found to be 0.03761.

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The optimum quantity of P_2O_5 to be applied per acre is at the point of optimum yield, i.e., at the point where the gradient (dy/dx) is equal to 0.03761

Maximum values and optimum values are given in Table 2.

Correlations were established between the initial yields and the maximum yields, and between the initial yields and the optimum yields. These were to be expected and no important inferences could be drawn from them. There were no correlations between the soil test values and the absolute magnitudes of either the initial yields, the maximum yields or the optimum yields. The next logical step was to consider the yield responses.

The maximum yield response is the maximum yield minus the initial yield ; likewise, the optimum yield response is the optimum yield minus the initial yield. These results are also given in Table 2.

At this stage regression equations were obtained and correlations were established. The degree of concomitance was expressed either by linear regression equations or by curvilinear regression equations obtained by converting the values to logarithms and the following inferences were drawn.

1. There is a negative correlation between the maximum P_2O_5 to be applied per acre as fertilizer and the soil test values for available phosphorus. The regression equation is $y = -1.59x + 122.94$; the correlation coefficient which is significant at one per cent. is -0.8852 . This is graphically shown in Figure 1.

2. The maximum yield responses and the soil test values for available phosphorus are connected by the equation $\log y = 9.953 - 2.241 \log x$. The correlation coefficient between $\log y$ and $\log x$ is -0.9001 and is significant at one per cent. This is graphically shown in Figure 2.

3. The relationship between the maximum yield responses and the maximum P_2O_5 to be applied as fertilizer is governed by the equation $\log y = -7.721 + 2.398 \log x$. The correlation coefficient which is significant at one per cent. is 0.9554 . This is graphically shown in Figure 3.

4. The optimum P_2O_5 to be applied as fertilizer and the soil values for available phosphorus are negatively correlated and given by the equation $y = -1.78x + 120.52$. The correlation coefficient which is significant at one per cent. is -0.9181 . This is graphically shown in Figure 4.

5. The optimum yield responses and the soil values for available phosphorus are connected by the equation $\log y = 10.408 - 2.388 \log x$. The correlation which is significant at one per cent. is -0.9108 . This is graphically shown in Figure 5.

6. The equation connecting the optimum yield responses and the optimum fertilizer P_2O_5 to be applied is $\log y = -5.642 + 1.976 \log x$. The correlation coefficient which is significant at one per cent. is 0.9807 . This is graphically shown in Figure 6.

It is worth noting that the correlation coefficients obtained with optimum values are bigger than those obtained with maximum values.

In order to use the soil test value for available phosphorus for the purpose of predicting the optimum quantity of fertilizer phosphorus to be applied and the optimum yield response to be expected therefrom, it is necessary to obtain an equation connecting these three variables. For this purpose and for the sake of uniformity a new equation using logarithms was obtained showing the relationship between available soil phosphorus (x) and the optimum quantity of fertilizer phosphorus to be applied (y) as the other two linear regressions were obtained on the logarithmic scale. This equation is $\log y = 7.969 - 1.163 \log x$. The correlation coefficient which is -0.8849 , though slightly lower than that obtained for untransformed values which was -0.9181 , is nevertheless significant at one per cent. This is graphically shown in Figure 7.

The multilinear regression equation between optimum yield response (y), available soil phosphorus (x_1) and the optimum quantity of fertilizer phosphorus to be applied (x_2) was then calculated and found to be $\log y = -3.148 - 0.409 \log x_1 + 1.701 \log x_2$ and the multiple correlation coefficient R which is significant at one per cent. is 0.6763 . It should be noted that in the above equation when the soil test value for available phosphorus has been determined, the optimum quantity of fertilizer P_2O_5 to be applied is fixed and the optimum yield response to be expected therefrom is also fixed.

Of the three variables, the available soil phosphorus is the most independent, then comes the optimum quantity of fertilizer phosphorus, and the most dependent variable is the optimum yield response. Therefore in the multilinear regression equation $\log y = -3.148 - 0.409 \log x_1 + 1.701 \log x_2$ values obtained from the equation ($\log x_2 = 7.969 - 1.163 \log x_1$) connecting the optimum quantity of fertilizer phosphorus to be used and the soil value for available phosphorus were substituted and the corresponding optimum yield responses were obtained. These yield responses and the yield responses obtained from the equation connecting the optimum yield responses and the available soil phosphorus values ($\log y = 10.408 - 2.388 \log x_1$) were not significantly different when tested by the method of Chi-Square. In the same manner these yield responses were compared with the yield responses obtained from the equation connecting the optimum yield responses and the optimum quantities of fertilizer phosphorus to be applied ($\log y = -5.642 + 1.976 \log x_2$) and were found to be not significantly different. There for practical purposes figures 7, 5 and 6 could be use for prediction.

From figure 7 it is possible to predict the optimum quantity of fertilizer P_2O_5 to be applied per acre to a particular soil when the available phosphorus of the soil as determined by the $NaHCO_3$ method of Olsen is known. Similarly from figure 5 the optimum yield response that could be expected for a particular soil

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test value could be predicted ; and likewise from figure 6, the optimum yield response that could be expected from the application of the optimum quantity of fertilizer P_2O_5 per acre could be predicted.

Further examination revealed that there is a relationship between the initial increases in yield per pound of P_2O_5 added and the soil test values for available phosphorus. The initial increase in yield is the gradient of the equation when x is equal to 0, i.e., the value of dy/dx when x is equal to 0, which, it will be seen, is equal to b of the equation $y = a + bx + cx^2$. The equation governing the different values of b and the corresponding soil values for available phosphorus is $\log y = 3.555 - 1.387 \log x$; the correlation coefficient which is significant at one per cent. is -0.8808 . This is graphically shown in Figure 8. This result leads to the conclusion that when the soil value for available phosphorus is low the initial increase in yield brought about by the application of phosphorus fertilizer is high and vice versa.

The results of these trials also indicate that the percentage yield concept as enunciated by Bray (1948) and referred to earlier is not applicable under these circumstances.

The methods of planting and the varieties used at the respective locations are given in Table 2. It was row sown in 13 locations, broadcast in 8, and transplanted in 4. It is very probable that the different methods of planting adopted have affected in some degree the absolute values of some of the yields obtained in the course of the experiment. As these trials have not been designed to evaluate the benefit to be derived from the adoption of different methods of planting no definite conclusions can be drawn with regard to this aspect of the problem. However, judging from past experience it would be reasonable to conclude that there would have been appreciable differences in the absolute magnitudes of the yields if a different method of planting had been adopted at a particular location. On the other hand, since the correlations obtained relate to yield responses it is a fair inference that the magnitude of these responses would have been the same whatever the method of planting may have been. That is, if a different method of planting had been adopted at a particular location the yield-fertilizer curve would have been parallel to the original curve and the phosphorus fertilizer requirements of the location would be the same whatever the method of planting may be.

The effect of application of fertilizer when different varieties are used are, by contrast, more important and more interesting. In Ceylon varieties are divided into two main groups, fertilizer responsive varieties and fertilizer non-responsive varieties ; all village varieties and some of the recommended

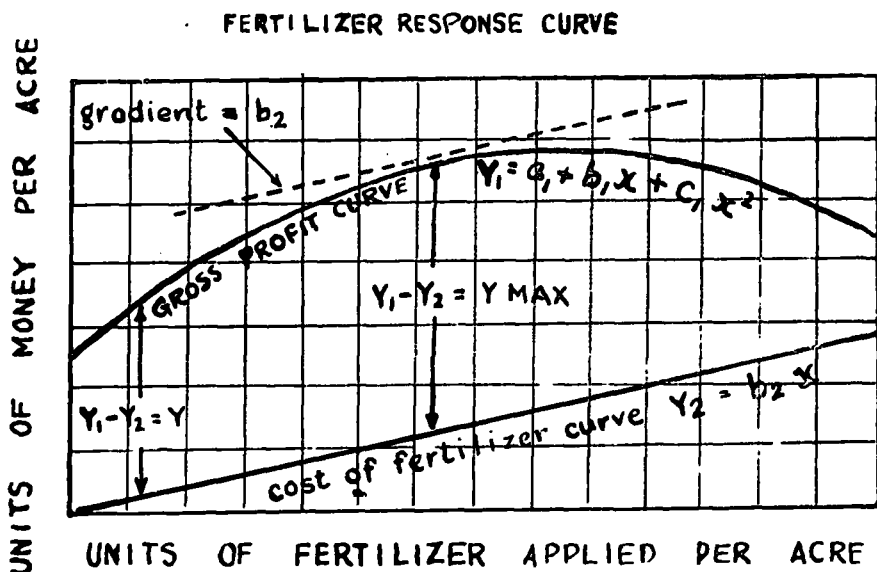
varieties are classified as fertilizer non-responsive and are given a much lesser quantity of fertilizer (N, P and K) than the fertilizer responsive varieties. When these trials were laid down, the extension officers who assisted in conducting them were requested to select a variety best suited to the area, and in the expectation that fertilizer responsive varieties would be used arrangements were made to apply the quantities of nitrogen and potassium recommended for fertilizer responsive varieties. However, in 13 of the 25 locations fertilizer non-responsive varieties were used and were given the quantities of nitrogen and potassium recommended for fertilizer responsive varieties. The fertilizer responsive varieties used were H4, H 501 and 61-555 ; the rest were fertilizer non-responsive. Among the latter group were Pachchaimperumal, a variety recommended by the Department of Agriculture, and such local varieties as Suduwi, Kottiaran, Thavalu and Dickwi.

It appears that all these fertilizer non-responsive varieties responded well to the levels of nitrogen and potassium that are recommended for fertilizer responsive varieties without lodging or any visual symptoms of disease or other adverse effects. Since the response to fertilizers of local varieties appear to have been evaluated using basal applications of fertilizers the encouraging response of local varieties in this trial appears to be due to the applications of top-dressings of nitrogen as against basal applications. This does not of course, mean that the fertilizer non-responsive varieties are as good as the fertilizer responsive varieties so far as their yield potentialities are concerned, but it clearly reveals that the recommendations of nitrogen and potassium for local varieties are erroneous. It is also likely that the fertilizer responsive varieties have a better grain producing efficiency and that the nitrogen and potassium recommendations for them could be profitably increased.

With regard to phosphorus, the experiment showed that the different varieties used contributed almost equally to the final result. This means that the requirements of phosphorus fertilizer, at the levels of nitrogen and potassium applied, are the same for all varieties and are dependent on the soil test values for available phosphorus. Here again, the argument must not be taken to mean that the fertilizer responsive varieties are not better yielders than the fertilizer non-responsive varieties ; it is very likely that the grain producing efficiency of the fertilizer responsive varieties is higher than that of the fertilizer non-responsive varieties, but what is striking is that the fertilizer phosphorus requirements, under the levels of nitrogen and potassium tested, appear

PREDICTION OF THE PHOSPHORUS FERTILIZER NEEDS OF RICE

to be the same for all varieties and depends only on the soil test values for available phosphorus. These conclusions would appear to point to the need for an immediate reassessment of the fertilizer requirements and a revaluation of the fertilizer responsiveness of the local varieties.



The grain yields in bushels per acre and the amounts of fertilizer P_2O_5 applied per acre were shown to be connected by the equation $y = a + bx + cx^2$. A new equation $y_1 = a_1 + b_1x + c_1x^2$ could be derived, where y_1 is the gross profit per acre and x the quantity of fertilizer P_2O_5 applied. This together with the cost of fertilizer curve $y_2 = b_2x$ is shown in the diagram above.

By definition the optimum yield is at the point where the gradient (dy/dx) is equal to one bushel per acre divided by the amount of fertilizer, the cost of which is Rs. 12, i.e., at the point where the gradient of the gross profit $y_1 = a_1 + b_1x + c_1x^2$ is equal to the gradient of the cost of fertilizer curve $y_2 = b_2x$.

$$\begin{aligned} \text{that is } b_1 + 2c_1x &= b_2 \\ \text{or } b_1 - b_2 + 2c_1x &= 0 \dots \dots \dots (1) \end{aligned}$$

The net profit is $y_1 - y_2$ and is given by the equation $y = a_1 + (b_1 - b_2)x + c_1x^2$. This equation has a maximum at the point where $dy/dx = 0$.

$$dy/dx = b_1 - b_2 + 2c_1x = 0 \dots \dots \dots (2)$$

Since equations (1) and (2) are identical, it is evident that the point of optimum yield is also the point of maximum profit.

Summary

Fertilizer trials were conducted in cultivators' fields in 25 locations scattered over various parts of Ceylon with dressings of phosphorus ranging from 0 to 120 lb. P_2O_5 per acre over basal dressings of nitrogen and potassium as recommended by the Department of Agriculture. With every soil tested the grain yields increased with increases in the levels of phosphorus applied, reached a maximum and then decreased notwithstanding the continued increase in the level of fertilizer phosphorus applications. The grain yields (y) in bushels per acre and the amounts of fertilizer (x) in lb. P_2O_5 per acre fitted the second degree polynomial $y=a+bx+cx^2$ with c small and negative. Different soils gave different values for the parameters a , b and c . The available P_2O_5 of the soils was determined by the sodium bicarbonate method of Olsen.

Maximum yield is at the point where the gradient (dy/dx) of the equation $y=a+bx+cx^2$ is equal to zero, and the maximum quantity of fertilizer phosphorus to be applied is at the point of the maximum yield. The economically optimal yield is defined as the yield where the gradient (dy/dx) is equal to one bushel per acre divided by the amount of fertilizer P_2O_5 , the cost of which is twelve rupees (the guaranteed price of a bushel of paddy is twelve rupees) and the economically optimal quantity of fertilizer phosphorus to be applied is at the point of the optimum yield.

Graphs were drawn, regression equations obtained, and correlations were established. The degree of concomittance was expressed by linear regression equations and by curvilinear regression equations obtained by converting the values to logarithms as shown below.

y		x	equation
1. Maximum P_2O_5 to be applied as fertilizer	Available values	P_2O_5 —Soil	$y = -1.59x + 122.94$
2. Maximum yield response	.. Available values	P_2O_5 —Soil	$\log y = 9.953 - 2.241 \log x$
3. Maximum yield response	.. Maximum applied	P_2O_5 to be as fertilizer	$\log y = -7.721 + 2.398 \log x$
4. Optimum P_2O_5 to be applied as fertilizer	Available values	P_2O_5 —Soil	$y = -1.78x + 120.52$
5. Optimum yield response	.. Available values	P_2O_5 —Soil	$\log y = 10.408 - 2.388 \log x$
6. Optimum yield response	.. Optimum applied as fertilizer	P_2O_5 to be as fertilizer	$\log y = -5.642 + 1.976 \log x$
7. Optimum P_2O_5 to be applied as fertilizer	Available values	P_2O_5 —Soil	$\log y = 7.969 - 1.163 \log x$

The variables in equations 4 and 7 are the same. In equation 7 the data were transformed to logarithms to obtain a multilinear regression equation between the optimum yield response (y), available soil phosphorus (x_1) and the

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optimum quantity of fertilizer phosphorus to be applied (x_2). This equation is $\log y = -3.148 - 0.409 \log x_1 + 1.701 \log x_2$.

For practical purposes equations 7, 5 and 6 could be used to predict the economically optimal quantity of phosphorus fertilizer to be applied to rice soils and the yield response to be expected therefrom when the soil analytical value for available phosphorus is known. The optimum yield was shown to be at the point of maximum profit.

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Figure 1:

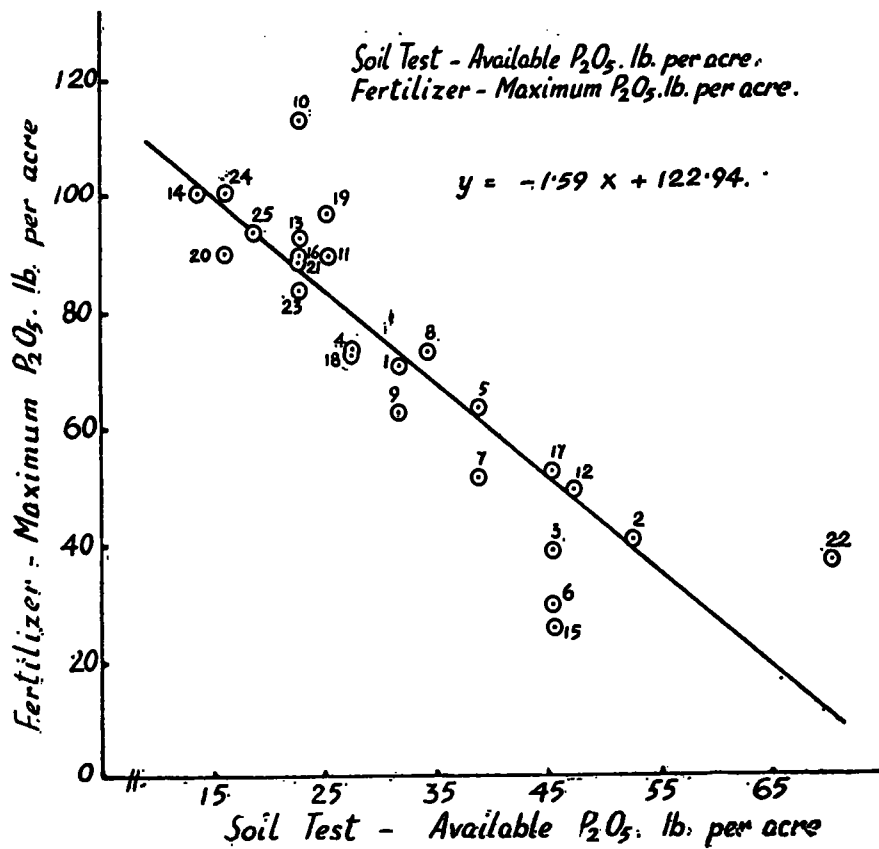
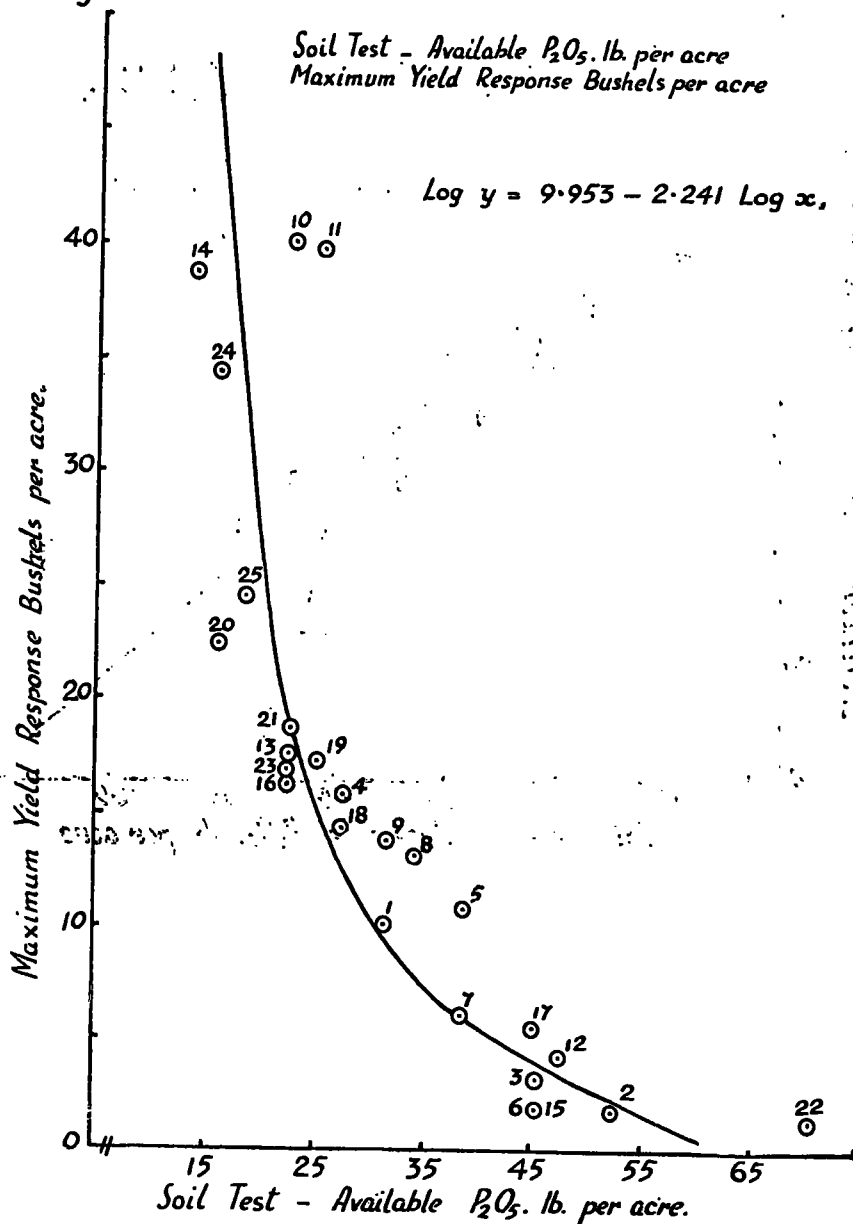


Figure 2.



PREDICTION OF THE PHOSPHORUS FERTILIZER NEEDS OF RICE

Figure 3

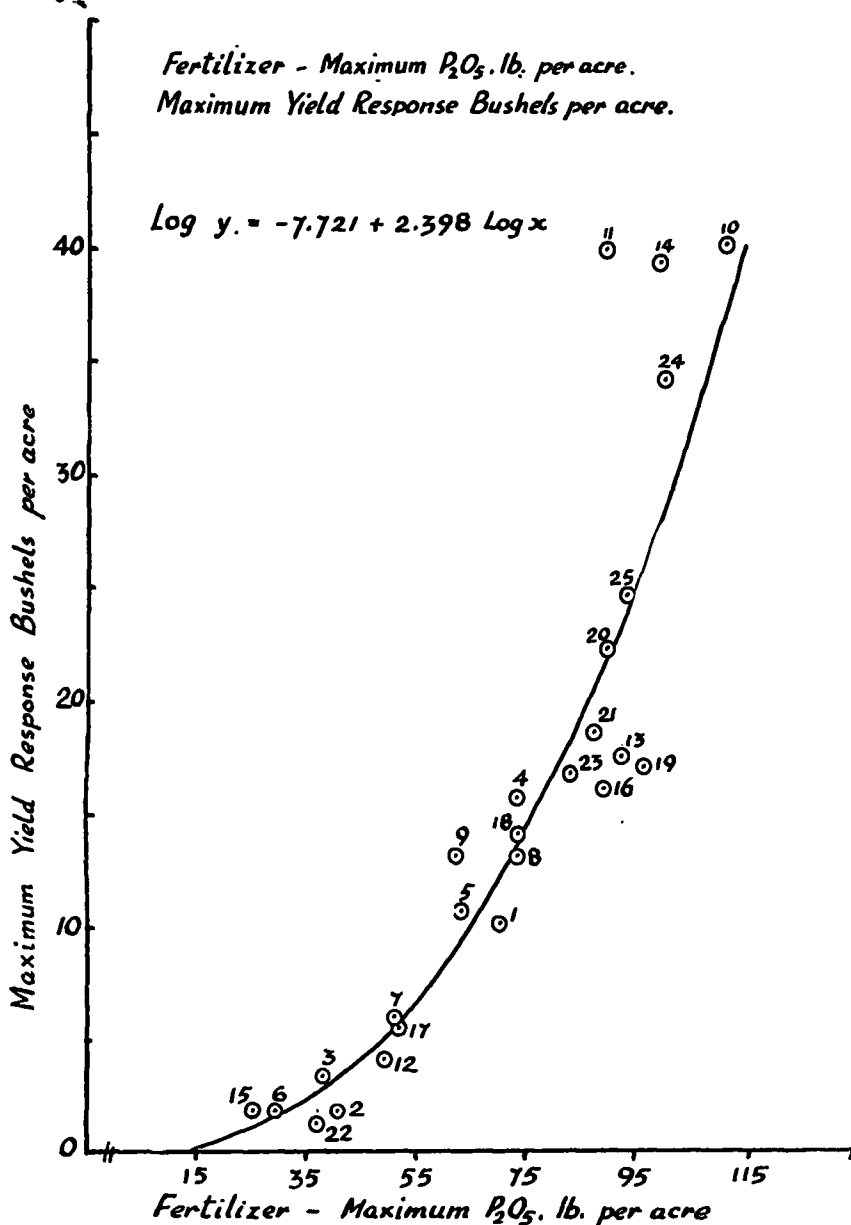
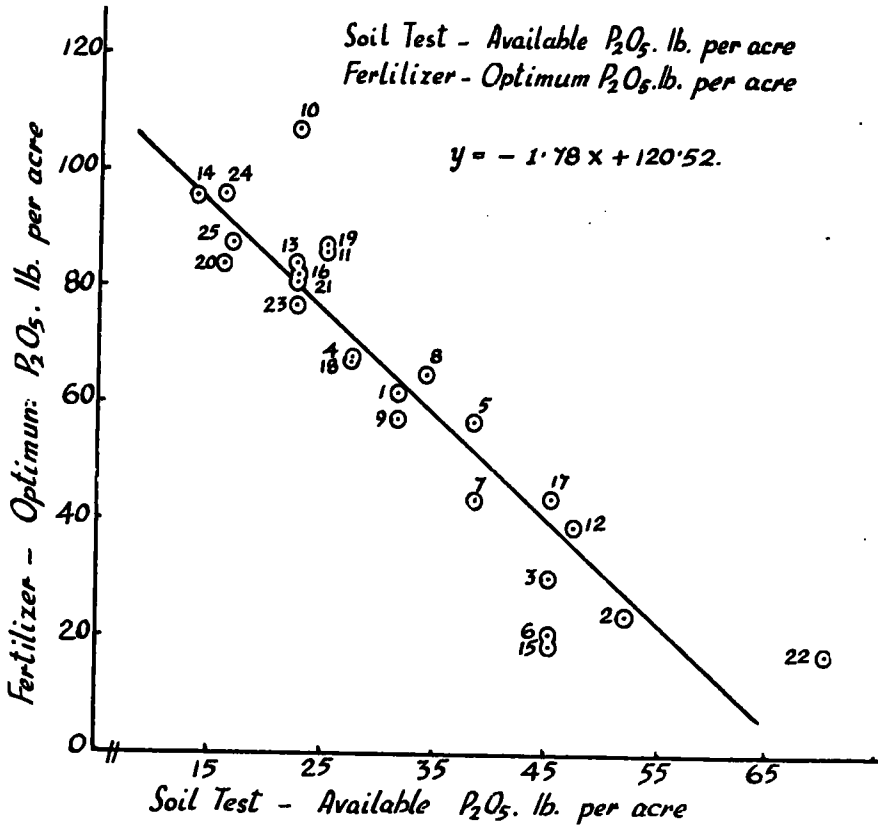


Figure 4



PREDICTION OF THE PHOSPHORUS FERTILIZER NEEDS OF RICE

Figure 5.

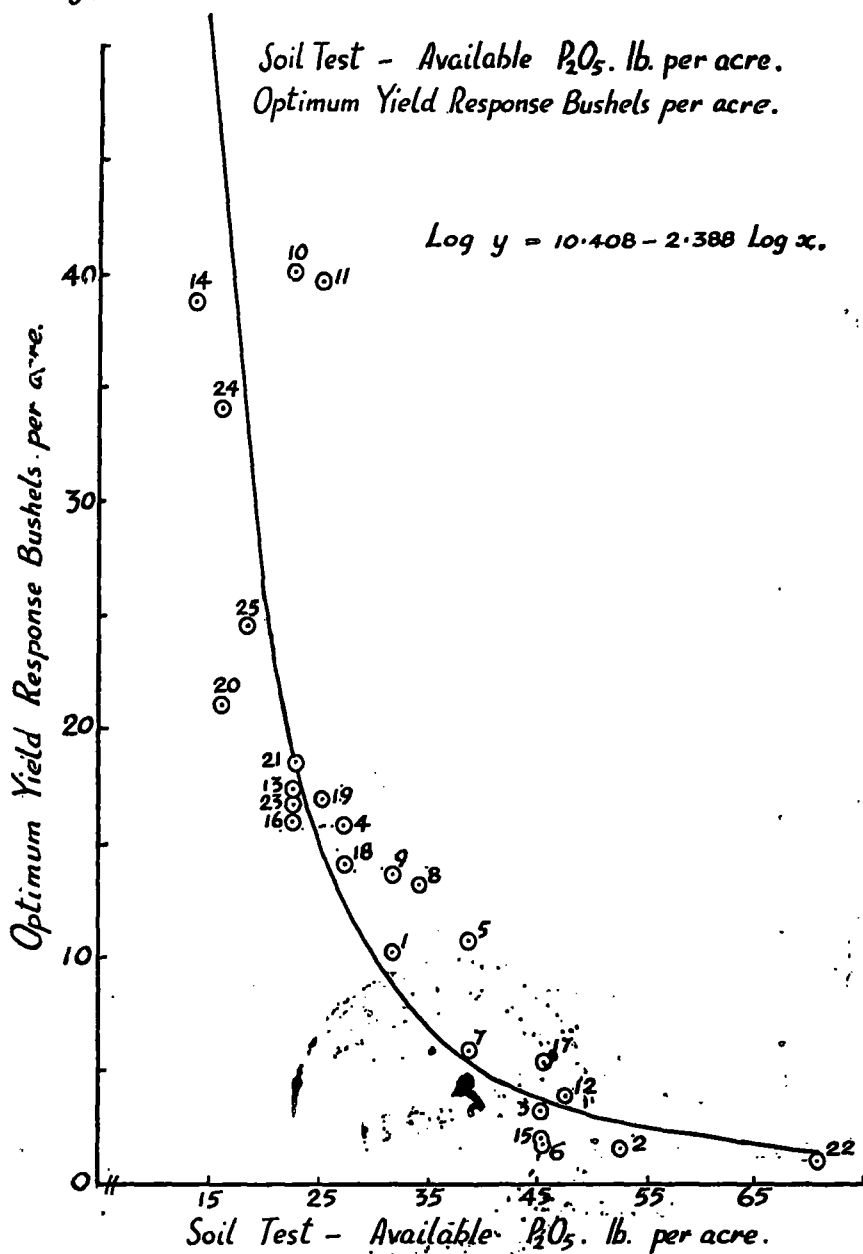
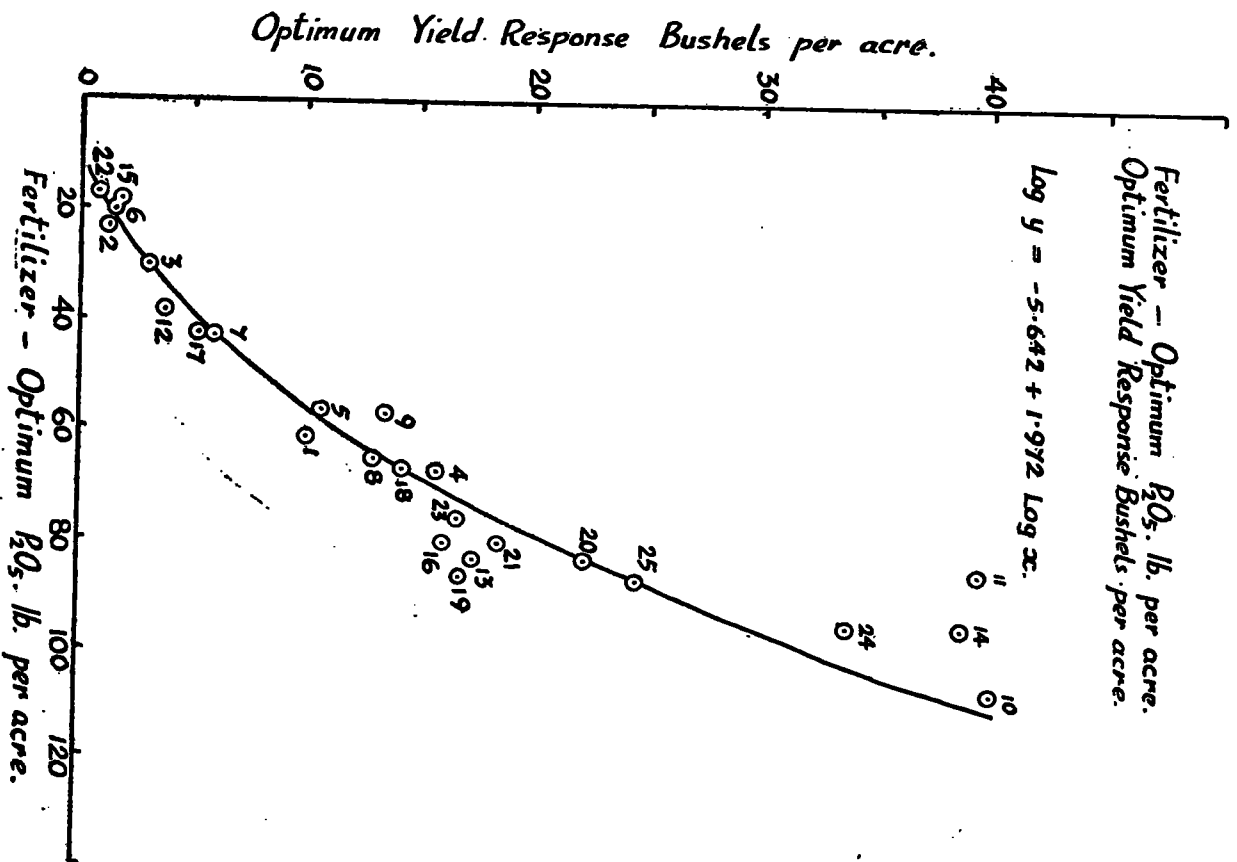


Figure 6.



PREDICTION OF THE PHOSPHORUS FERTILIZER NEEDS OF RICE

Figure 7

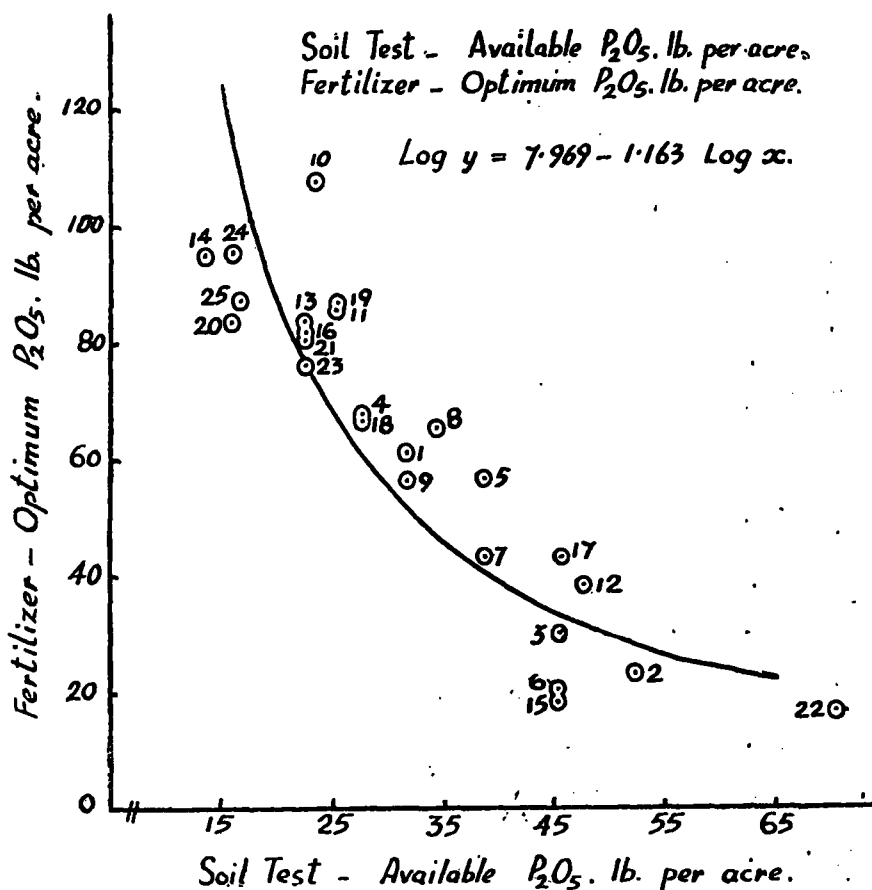


Figure 8.

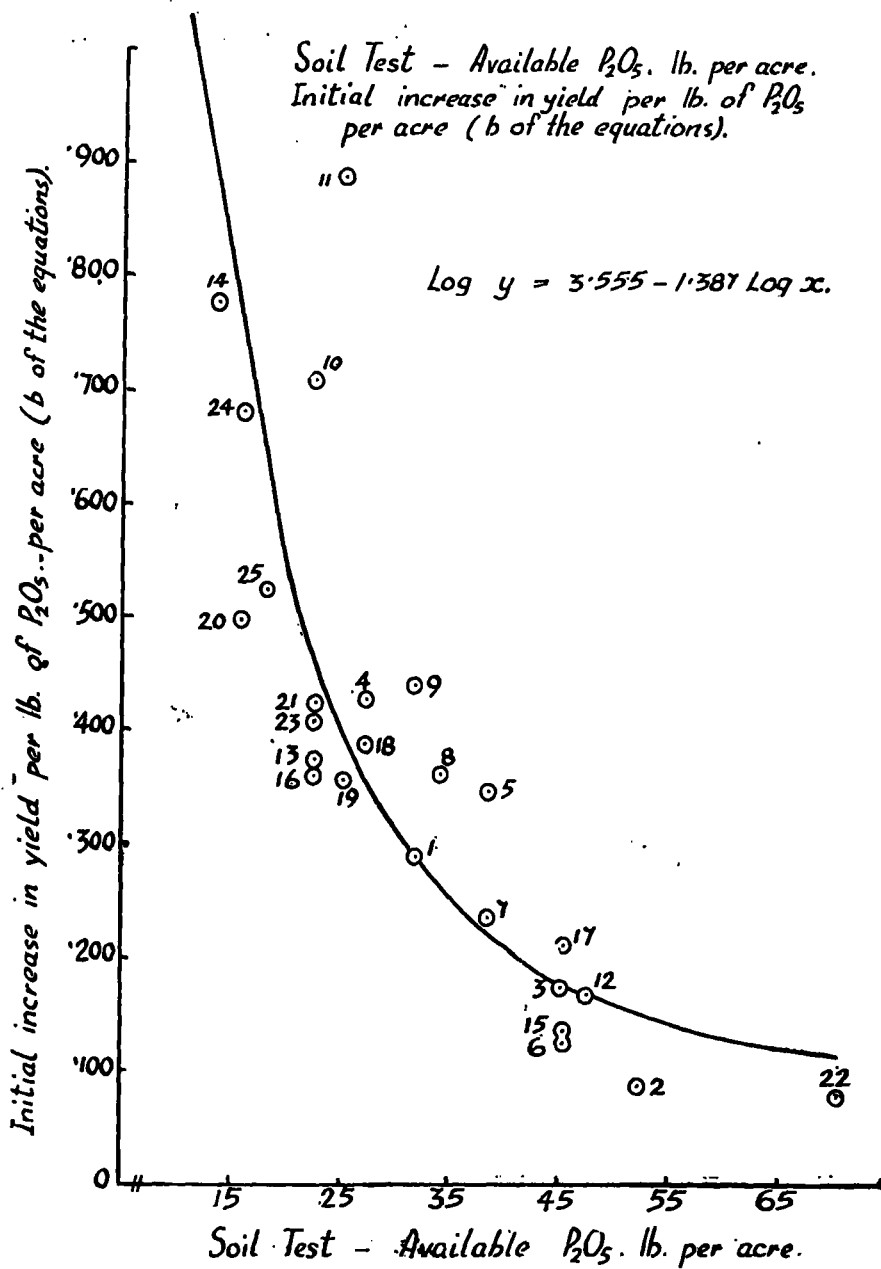


TABLE 1.—Soil Analysis

No.	Location		pH	Organic matter %	Nitro- gen %	c. e. c. m. e. per 100 gm.	t. e. b. m. e. per 100 gm.	Available P_2O_5 lb/acre	Available silica ppm. SiO_2	Texture
1 ..	Matara	I ..	4.9 ..	3.7 ..	.18 ..	15.5 ..	3.9 ..	31.9 ..	218 ..	Sandy Clay Loam
2 ..	Matara	II ..	4.4 ..	7.1 ..	.35 ..	26.4 ..	6.2 ..	52.4 ..	273 ..	Sandy Clay
3 ..	Galle	I ..	4.8 ..	7.9 ..	.36 ..	25.2 ..	6.3 ..	45.6 ..	145 ..	Sandy Clay
4 ..	Galle	II ..	5.0 ..	26.1 ..	.78 ..	18.6 ..	6.1 ..	27.4 ..	145 ..	Humic Soil
5 ..	Kalutara		5.0 ..	25.6 ..	.68 ..	16.8 ..	3.9 ..	38.8 ..	161 ..	Humic Soil
6 ..	Colombo	I ..	4.7 ..	2.1 ..	.08 ..	9.1 ..	2.4 ..	45.0 ..	16 ..	Sandy Clay Loam
7 ..	Colombo	II ..	5.1 ..	5.0 ..	.16 ..	13.8 ..	2.4 ..	38.8 ..	32 ..	Sandy Loam
8 ..	Colombo	III ..	4.5 ..	2.9 ..	.13 ..	13.9 ..	3.1 ..	34.2 ..	128 ..	Sandy Clay
9 ..	Colombo	IV ..	4.7 ..	2.6 ..	.13 ..	13.9 ..	2.5 ..	31.9 ..	170 ..	Sandy Clay
10 ..	Ratnapura		5.0 ..	4.4 ..	.17 ..	16.3 ..	2.4 ..	22.8 ..	90 ..	Sandy Clay Loam
11 ..	Kegalle		5.1 ..	6.5 ..	.24 ..	16.6 ..	2.7 ..	25.1 ..	58 ..	Sandy Clay Loam
12 ..	Kurunegala	I ..	4.7 ..	2.4 ..	.12 ..	12.6 ..	2.4 ..	47.7 ..	48 ..	Sandy Loam
13 ..	Kurunegala	II ..	5.0 ..	2.6 ..	.13 ..	21.3 ..	6.0 ..	22.8 ..	218 ..	Sandy Clay
14 ..	Puttalam	I ..	5.5 ..	2.4 ..	.11 ..	22.7 ..	8.5 ..	13.7 ..	218 ..	Sandy Clay
15 ..	Puttalam	II ..	5.9 ..	3.3 ..	.15 ..	22.0 ..	9.9 ..	45.6 ..	135 ..	Sandy Clay Loam
16 ..	Polonnaruwa	I ..	5.6 ..	2.1 ..	.10 ..	18.5 ..	6.8 ..	22.8 ..	145 ..	Sandy Clay
17 ..	Polonnaruwa	II ..	6.1 ..	1.6 ..	.07 ..	16.2 ..	7.9 ..	45.6 ..	128 ..	Fine Sandy Loam
18 ..	Polonnaruwa	III ..	6.0 ..	2.6 ..	.11 ..	20.2 ..	8.7 ..	27.4 ..	257 ..	Sandy Clay Loam
19 ..	Polonnaruwa	IV ..	6.3 ..	2.1 ..	.13 ..	17.2 ..	11.8 ..	25.1 ..	209 ..	Clay Loam
20 ..	Vavuniya	I ..	5.6 ..	0.8 ..	.04 ..	6.2 ..	2.5 ..	16.0 ..	64 ..	Sandy Clay
21 ..	Vavuniya	II ..	7.8 ..	1.3 ..	.06 ..	15.8 ..	10.6 ..	22.8 ..	433 ..	Sandy Clay
22 ..	Vavuniya	III ..	6.2 ..	1.8 ..	.08 ..	13.6 ..	8.1 ..	70.7 ..	135 ..	Sandy Clay Loam
23 ..	Trincomalee		5.7 ..	1.6 ..	.06 ..	10.6 ..	5.4 ..	22.8 ..	103 ..	Sandy Clay
24 ..	Jaffna	I ..	5.6 ..	0.8 ..	.07 ..	10.7 ..	3.3 ..	16.0 ..	26 ..	Sandy Clay
25 ..	Jaffna	II ..	5.5 ..	1.3 ..	.08 ..	12.6 ..	6.9 ..	18.2 ..	106 ..	Silty Clay

TABLE 2—Yield—Fertilizer Equations. Maximum Values. Optimum Values, etc.

No.	Location	Variety of Paddy	Method of Planting	Equation	Avail- able P ₂ O ₅ lb/acre	Maxi- mum P ₂ O ₅ lb/acre	Maxi- mum Yield Bushels per acre	Maxi- mum Yield Res- ponse Bushels per acre	Opti- mum P ₂ O ₅ lb/acre	Opti- mum Yield Bushels per acre	Opti- mum Yield Res- ponse Bushels per acre
1 ..	Matara	I .. H 4	.. Row Sown	$y = 59.565 + 0.291x - 0.00206x^2$	31.9..	70.6..	69.8..	10.2..	61.5..	69.7..	10.1
2 ..	Matara	II .. H 501	.. Row Sown	$y = 53.868 + 0.088x - 0.00107x^2$	52.4..	41.0..	55.7..	1.8..	23.5..	55.3..	1.4
3 ..	Galle	I .. 61-555	.. Row Sown	$y = 75.169 + 0.173x - 0.00226x^2$	45.6..	38.3..	78.5..	3.3..	30.0..	78.3..	3.1
4 ..	Galle	II .. H 501	.. Broadcast	$y = 57.172 + 0.428x - 0.00289x^2$	27.4..	74.0..	73.0..	15.8..	67.5..	72.0..	15.7
5 ..	Kalutara	.. H 4	.. Row Sown	$y = 36.103 + 0.343x - 0.00271x^2$	38.8..	63.3..	47.0..	10.9..	56.3..	46.8..	10.7
6 ..	Colombo	I .. H 4	.. Row Sown	$y = 65.302 + 0.122x - 0.00206x^2$	45.6..	29.6..	67.1..	1.8..	20.5..	66.0..	1.6
7 ..	Colombo	II .. Suduwl	.. Broadcast	$y = 54.755 + 0.234x - 0.00226x^2$	38.8..	51.8..	60.8..	6.0..	43.4..	60.7..	5.9
8 ..	Colombo	III .. H 4	.. Broadcast	$y = 28.317 + 0.360x - 0.00245x^2$	34.2..	73.5..	41.5..	13.2..	65.8..	41.4..	13.1
9 ..	Colombo	IV .. H 4	.. Broadcast	$y = 32.281 + 0.439x - 0.00353x^2$	31.9..	62.2..	45.9..	13.6..	56.9..	45.8..	13.5
10 ..	Ratnapura	.. Kottiaran	.. Row Sown	$y = 18.045 + 0.709x - 0.00314x^2$	22.8..	112.0..	59.0..	40.1..	106.9..	58.9..	40.0
11 ..	Kegalle	.. Thavalu	.. Row Sown	$y = 20.203 + 0.889x - 0.00499x^2$	25.1..	89.1..	50.8..	39.6..	85.3..	59.7..	39.5
12 ..	Kurunegala	I .. H 4	.. Transplanted	$y = 57.604 + 0.168x - 0.00170x^2$	47.7..	49.4..	61.8..	4.2..	38.4..	61.5..	3.9
13 ..	Kurunegala	II .. H 4	.. Transplanted	$y = 82.082 + 0.377x - 0.00203x^2$	22.8..	92.9..	99.6..	17.5..	83.6..	99.4..	17.3
14 ..	Puttalam	I .. Pachchal-perumal	.. Broadcast	$y = 30.153 + 0.777x - 0.00388x^2$	13.7..	100.1..	69.1..	38.9..	95.3..	69.0..	38.8
15 ..	Puttalam	II .. Pachchal-perumal	.. Row Sown	$y = 37.142 + 0.137x - 0.00260x^2$	45.6..	25.6..	38.9..	1.8..	18.5..	38.8..	1.7
16 ..	Polonnaruwa	I .. Pachchal-perumal	.. Broadcast	$y = 42.326 + 0.360x - 0.00201x^2$	22.8..	89.6..	58.4..	16.1..	80.2..	58.3..	16.0
17 ..	Polonnaruwa	II .. Dikwli	.. Transplanted	$y = 76.107 + 0.210x - 0.00200x^2$	45.6..	52.5..	81.6..	5.5..	43.1..	81.4..	5.3
18 ..	Polonnaruwa	III .. Pachchal-perumal	.. Row Sown	$y = 38.475 + 0.386x - 0.00261x^2$	27.4..	73.0..	52.7..	14.2..	66.7..	52.6..	14.1
19 ..	Polonnaruwa	IV .. H 4	.. Transplanted	$y = 94.371 + 0.356x - 0.00185x^2$	25.1..	96.2..	111.5..	17.1..	86.1..	111.3..	16.9
20 ..	Vavuniya	I .. Pachchal-perumal	.. Row Sown	$y = 31.880 + 0.407x - 0.00276x^2$	16.0..	90.0..	54.3..	22.4..	83.2..	54.1..	22.2
21 ..	Vavuniya	II .. Pachchal-perumal	.. Broadcast	$y = 43.735 + 0.423x - 0.00204x^2$	22.8..	88.1..	62.4..	18.7..	80.3..	62.2..	18.5
22 ..	Vavuniya	III .. H 4	.. Row Sown	$y = 62.270 + 0.072x - 0.00097x^2$	70.7..	37.0..	63.6..	1.3..	17.7..	63.2..	0.9
23 ..	Trincomalee	.. Pachchal-perumal	.. Broadcast	$y = 66.150 + 0.404x - 0.00241x^2$	22.8..	83.8..	83.1..	16.9..	76.0..	82.9..	16.7
24 ..	Jaffna	I .. Pachchal-perumal	.. Row Sown	$y = 24.474 + 0.680x - 0.00337x^2$	16.0..	100.9..	58.8..	34.3..	95.3..	58.7..	34.2
25 ..	Jaffna	II .. Pachchal-perumal	.. Row Sown	$y = 41.842 + 0.524x - 0.00279x^2$	18.2..	93.9..	66.4..	24.6..	87.2..	66.3..	24.5