

Th.J. Ferrari
Institute for Soil Fertility - Haren (Gr)

Introduction

In the study of soil fertility we meet a complex and dynamic system. This system is characterized not only by a great number of variables but also by numerous relationships. Besides, the system is not constant but changes during time.

From the beginning the method of natural sciences has been applied in the soil fertility research. This means that one or more factors are changed artificially by the researcher and the other factors are kept constant as far as possible. This view has developed the well-known pot and field experiments. The field experiment has the great advantage that it agrees best with reality by which extrapolation of the results to practice is less dangerous in this respect. On the other hand it has the disadvantage that the assumption of constancy of the other factors is rather doubtful and the conditions of the experiment are largely unknown. This means that results of field experiments are explainable only with difficulty and should be applied with caution. These limits can be characterized best by the words of Bradfield on the occasion of the 25th anniversary of the Soil Science Society of America in 1961: "It seems to me that we cannot escape the conclusion that the reason we continue to investigate and reinvestigate certain aspects of soil fertility is, that we are not yet able to predict with confidence what will happen in the case we are interested in, because there are too many parameters involved which we are still unable to identify, measure or interpret." Somewhat further on he already indicates the way taken wrongly: "The old classical dictum of experimental science of studying one factor at the time by holding all factors constant except the one under study and then vary it systematically, is very good in the laboratory; but it is always difficult, and in many cases almost impossible, in the soil fertility studies involving the growing of crops on soils in either field or greenhouse".

The soil fertility research in the Netherlands has developed its own methodology and obtained important results.

Soil fertility as a more-dimensional system

It is a common experience that the results of a number of field experiments under apparently same conditions are always different. Whereas some research directions tried to find a solution for this difficulty in an increase of accuracy the Dutch school has worked from the beginning in a different way. The guiding idea has been that these differences must be considered not as accidental but as real ones; it is the task of the research to explain these differences by causal factors. A start was given by De Vries saying that the yield is a function of many factors and that soil fertility must be considered as a more-dimensional system.

An investigation into the factors determining the sizes of the increases and decreases of the pH of the soil by a continued nitrogen dressing has been of great importance for the further development. In this example an interaction has been investigated but one factor was not varied systematically. This example will be discussed in a little more detail as in the analysis some principles and techniques are applied which are characteristic for the later development.

This was the problem. From a number of perennial experimental fields the ultimate increase or decrease of pH, brought about in the soil by continued manuring of sulphate of ammonia or sodium nitrate, was known. The analysis showed that these increases and decreases were not equally large on the different fields. On some experimental fields the pH sharply increases by sulphate of ammonia, but on other fields it only showed a small increase. It has been a good thought to accept one particular characteristic of the soil as a cause of the differences between experimental fields and to correlate the results of the experiments in a certain way to this point of view. In this case Q_n was taken as the explanatory factor, that is to say the relation between the number of kilograms of nitrogen per ha and the number of tons of humus per ha of top layer. On account of special considerations on the pH finally reached an influence of that kind could have been expected. In fact a clear relationship between Q_n on the one side and the increases and decreases of pH on the other side was found. This is demonstrated by the two-dimensional graph of figure 1. In this way the hypothesis was confirmed and an estimate of the size of the influence was obtained. It was now possible to predict the changes in pH influenced by nitrogen dressing.

This example has been important for the further development. A number of principles and techniques has been applied which has stimulated the development of more-dimensional thinking.

Some principles and techniques used

The first point is the assumption that the soil and other characteristics to explain the differences between the experimental fields are present in a continuous range. In the last example this factor was the Q_n . It could also have been a range of increasing amounts of fertilizers or of different amounts of soil phosphate or potash between the field experiments. In that case the differences are not made artificially as these differences are given more or less naturally. The relationships between these growth factors and the dependent variables such as yield or soil pH may be described by a curve or by mathematical equation.

The way of taking variables in a continuous range has been supported strongly by the possibilities of the graphic analysis technique. Formerly as well as nowadays mathematical descriptions of most phenomena on the basis of physiological knowledge are lacking. The choice of the graphic method was not on foundations of principle; there was nothing better to be had. In the graphic method some definite relationships are assumed and it is investigated heuristically which types of curves describe best the relationships in question. There is no great difference between the mathematical and graphic methods in these matters. The logical restrictions of the graphic analysis are comparable to those which apply to the choice of the mathematical one. For the rest we have started to use the computer to do the graphical work.

The second principle used in our soil fertility studies is also present in the example. It is related with the fact that many soil factors can not be varied systematically or only with great difficulty. Which influences have clay or organic-matter content on the response on nitrogen dressing or on the yield? It is usual in experimental sciences to test hypotheses with data of experiments in which one or more variables are varied systematically and all the others are held constant. Two remarks can be made. The first one is that the assumption about the constancy of the other factors is a dangerous one. The researcher can expect that the interference itself changes a number of those other variables. Each conclusion about causality is a dangerous one in that case. The second remark is that it is not necessary for the logic of experimentation to change a factor artificially. An hypothesis can also be tested by non-experimental data. This point may be of importance if the meaning of factors such as ground-water depth, silt content or profile are investigated.

Research on fertilizer recommendations

The above mentioned ideas can be illustrated with results of the research about the fertilizer recommendation scheme. We take the phosphate for an example. For this kind of investigations a series of 30-40 experimental fields are laid out. On each field the same range of phosphate dressing levels is used, whereas the other nutrients are brought in optimal conditions. Regarding the choice of the fields care has been taken to obtain the largest possible differentiation between the experimental fields with respect to the phosphorus status and other factors expected to have an influence on the response.

Firstly the relationships between fertilizer amounts and yield on each field are determined graphically or numerically. It is important to find the point of the maximal yield. It appears further that the responses of the experimental fields differ among themselves. Some fields have a large response, whereas other fields have responded very little. In order to eliminate the influence of the yield level caused by other factors all yields of an experimental field are expressed in percentages of the maximal yield of this field. By this method the number of dimensions of the model is decreased strongly. A reasonable assumption is furthermore that the differences in phosphate content between the experimental fields are responsible for the differences in response. In order to test this assumption the relative yields of e.g. the plots without phosphate dressing are related to the corresponding phosphate content. If this assumption is true a relationship has to be found. An example is given in figure 2. A scattering of the points around the line means that the responses are smaller or greater than the average. A part of this scattering is due to experimental error, another part might be explained by influences of other factors. In that case we have a three- or more-dimensional model. Figure 3 gives a summary of the relationships found with various soil types.

It is possible to proceed with the analysis by doing the same analysis for other dressing levels. By this analysis the interaction is found between phosphate status of the soil and the amount of dressing. It appears from figure 4 that a shortage of phosphate in the soil can be removed with a certain dressing whereas on soils with a rich phosphate status no or less phosphate must be given to get the maximal yield. Such graphs are at the same time the basis of the fertilizer recommendation scheme. It is possible to gather from these graphs the amounts of phosphate fertilizer for each phosphate status and for each crop. Of course, this is a too simple diagram as besides phosphate other soil factors could be important. In order to take these factors into account more-dimensional graphs are necessary.

Further development

The ideas discussed up till now have always been guides for the later research in the Netherlands. Other problems such as the evaluation of fertilizers and organic materials, of methods and time of fertilizer application, of new chemical soil tests a.s.o. have been investigated in a similar way. This type of problems is rather simple as a crop response is studied; the elimination of the absolute yield level will limit the number of dimensions.

The model becomes more complex if the number of variables can not be limited. We meet this problem if the yield variation itself must be explained. This is an important problem in the Netherlands too as the yields of the farmers are diverging strongly. Into the model many variables have to be taken of which the values can not be varied systematically. The experimental data are obtained now from some hundred of simple plots of which yields and many soil characteristics are determined. A more-dimensional regression model is used to estimate the influence of the factors. By this method we succeeded to explain 88% of the variation of the yields of potatoes with the aid of thirteen factors. Figure 5 shows the agreement between experimental and calculated yields. Our knowledge about the optimal ground-water depth in the Netherlands is based on this type of studies.

The difficulties become even greater if the complexity of the model is increased by the number of relationships too. The experiment with interference and also the regression model are both characterized by the assumption that a change of an independent variable influences only the dependent variable and not the other independent factors. This assumption is represented by the use of only one equation. However, it has been our experience that this assumption is unrealistic in many cases. This means that a regression model is useless in such a case and that we have to use models with more equations. For this purpose the method of the path coefficients has been introduced by which it is possible to analyse such kind of problems. Figures 6 and 7 show the differences between these models. The purpose was to estimate the influences of the variables on which the MgO-content of the grass depends. In the last figure direct and indirect influences have been introduced which can be represented only by using more equations.

Up till now we have studied the problems as static and not as dynamic ones. In many cases this has been satisfying. But now we are meeting more and more problems for which the static assumption will not do. The dynamic behaviour means that differential equations have to be taken into the model. However, most differential equations do not have an analytical solution. At present it is possible to solve these models numerically with the aid of the computer and to do experiments with these models by the simulation technique. In this way we studied the leaching of nitrate in winter in relation to the amount of rain, ground-water depth and profile. The graph of figure 8 shows the agreement between experimental and calculated data over a period of 3 months.

Conclusion

In the beginning I referred to the complaint of Bradfield about the poor results of soil fertility studies. I am as well of the opinion that the most important reason for the poor results in many cases may be the too strong sticking to the method of physical sciences based on assumptions and models not in agreement with soil fertility reality. We have to realize this rule: the problem has to determine model and kind of experiment, and not reversed! This reversal has been the error in many soil fertility studies.

References

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Fig. 1. Relationship between ultimate pH and Q_n . Every dot represents one experimental field.

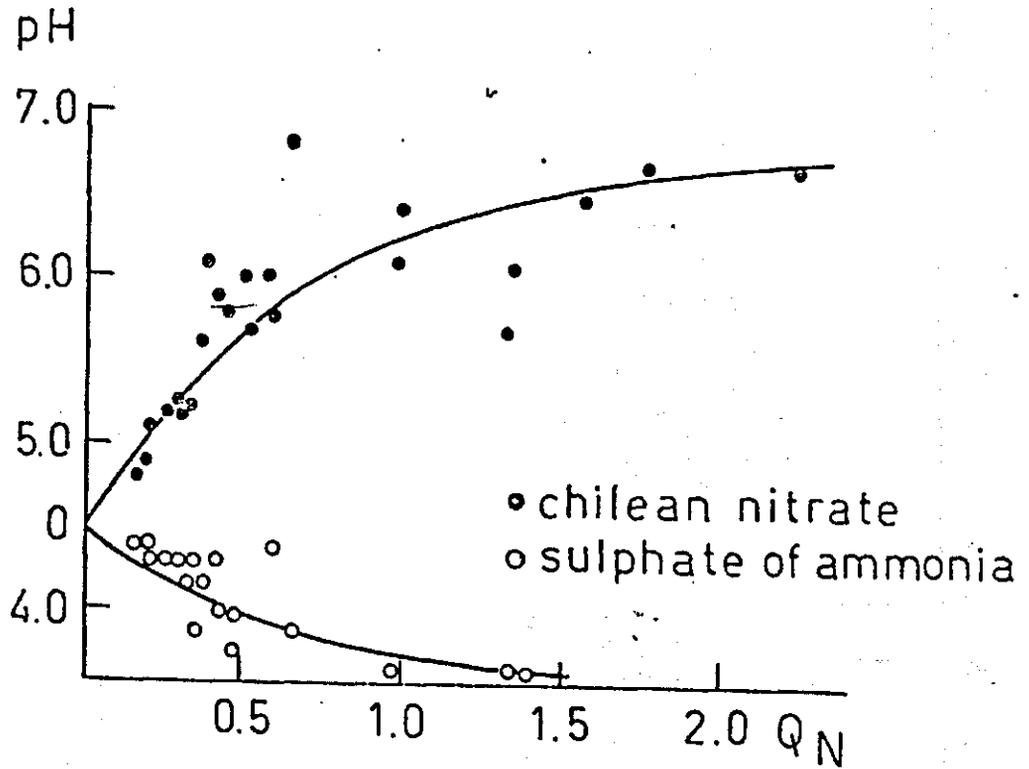


Fig. 2. Relationship between yield without phosphate dressing and phosphate status of the soil. Every dot represents one experimental field.

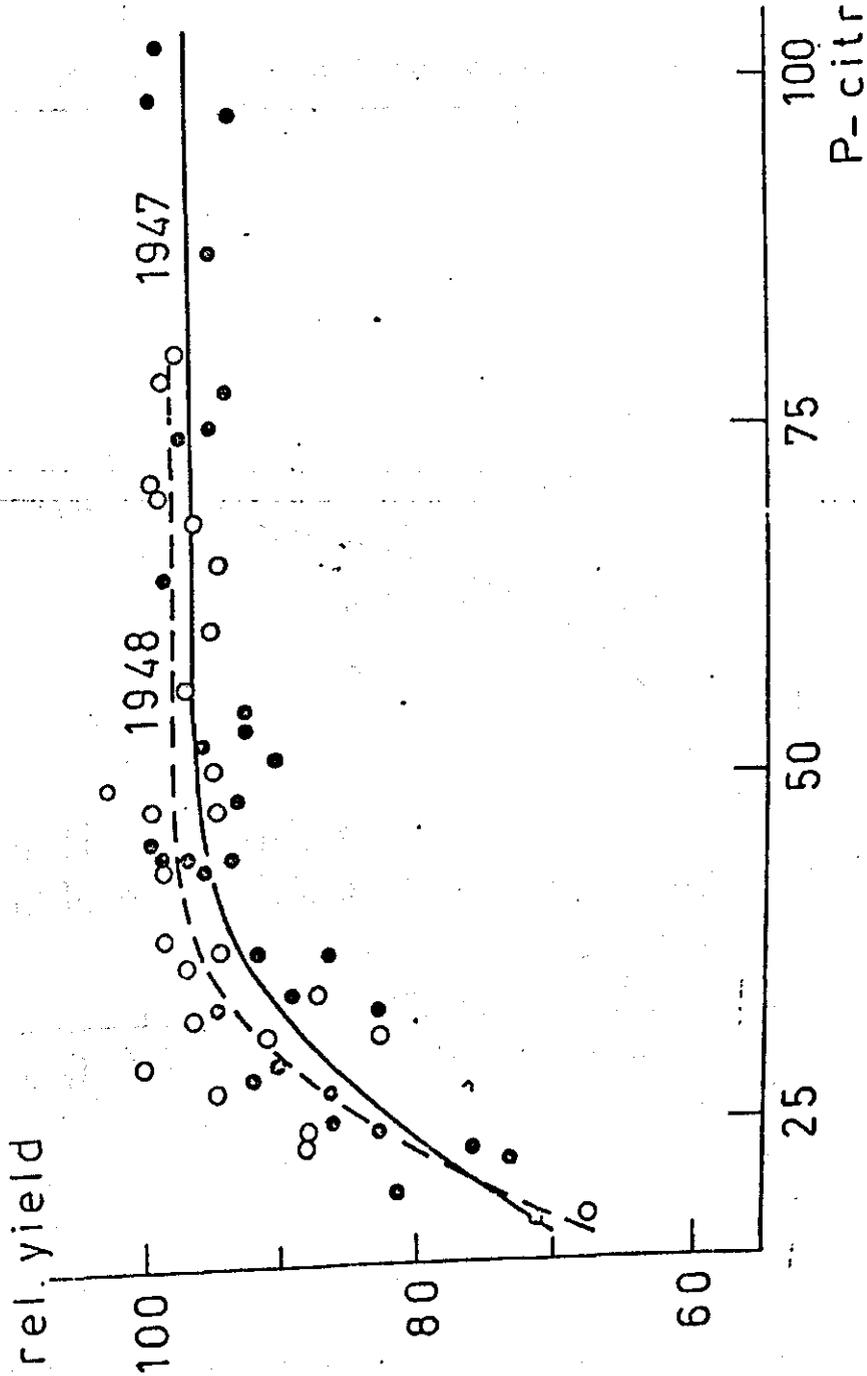


Fig. 3. The same relationship as in figure 2, respectively for loess, low peat, marine clay, river clay and sandy soils.

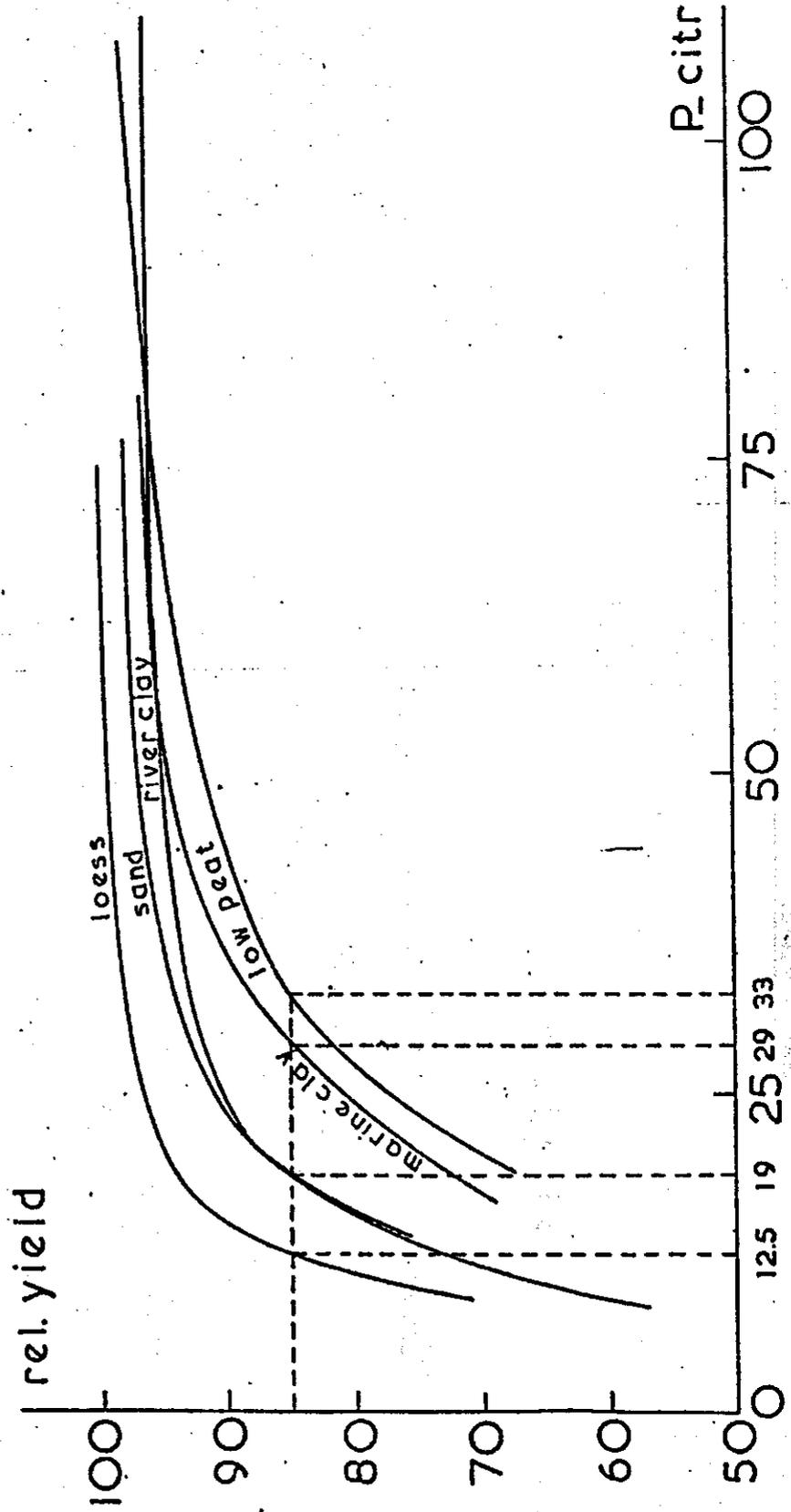


Fig. 4. Influences of phosphate status of the soil and phosphate dressing on yield.

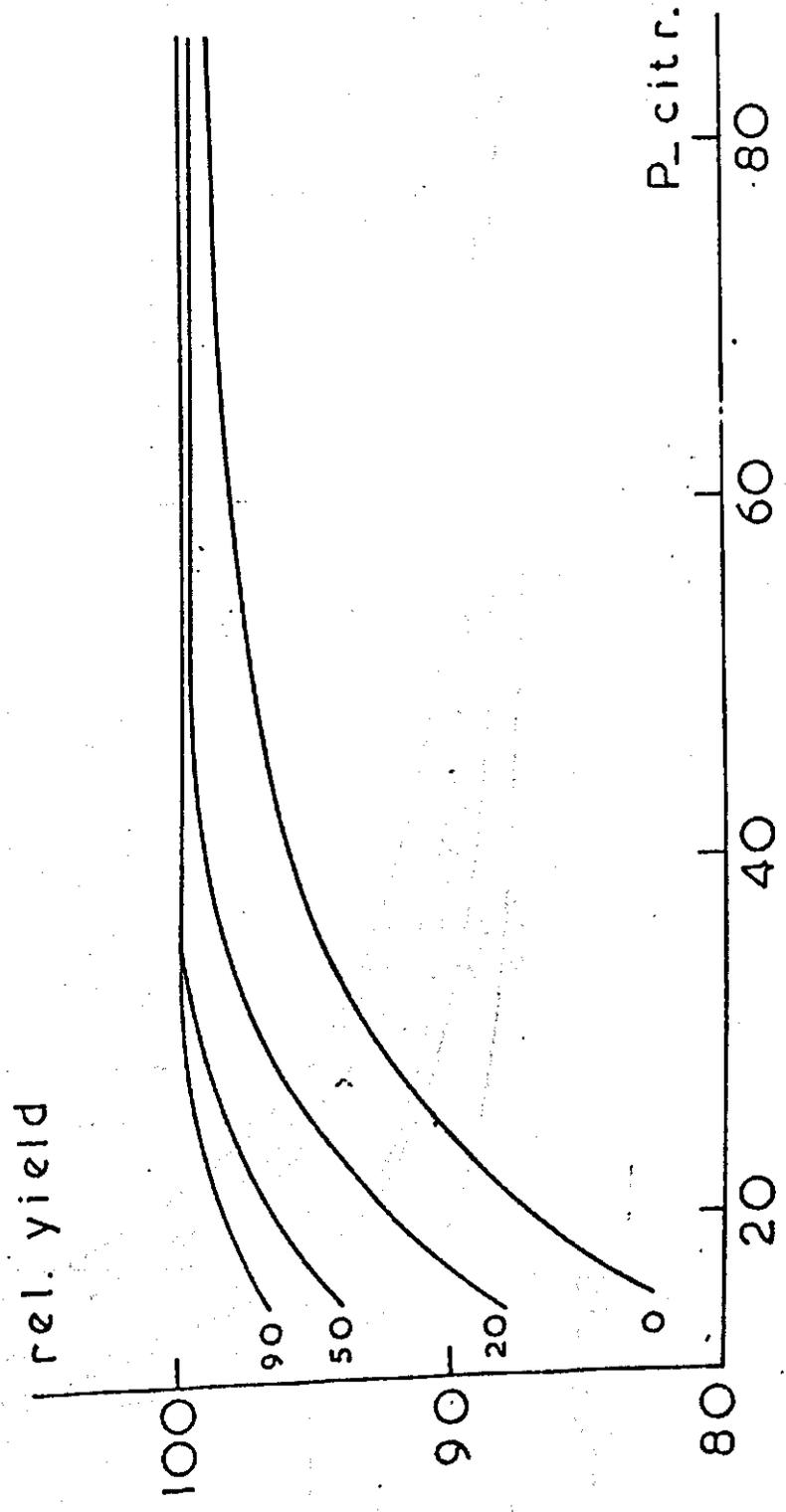


Fig. 5. Correlation between experimental and calculated yields of potatoes.

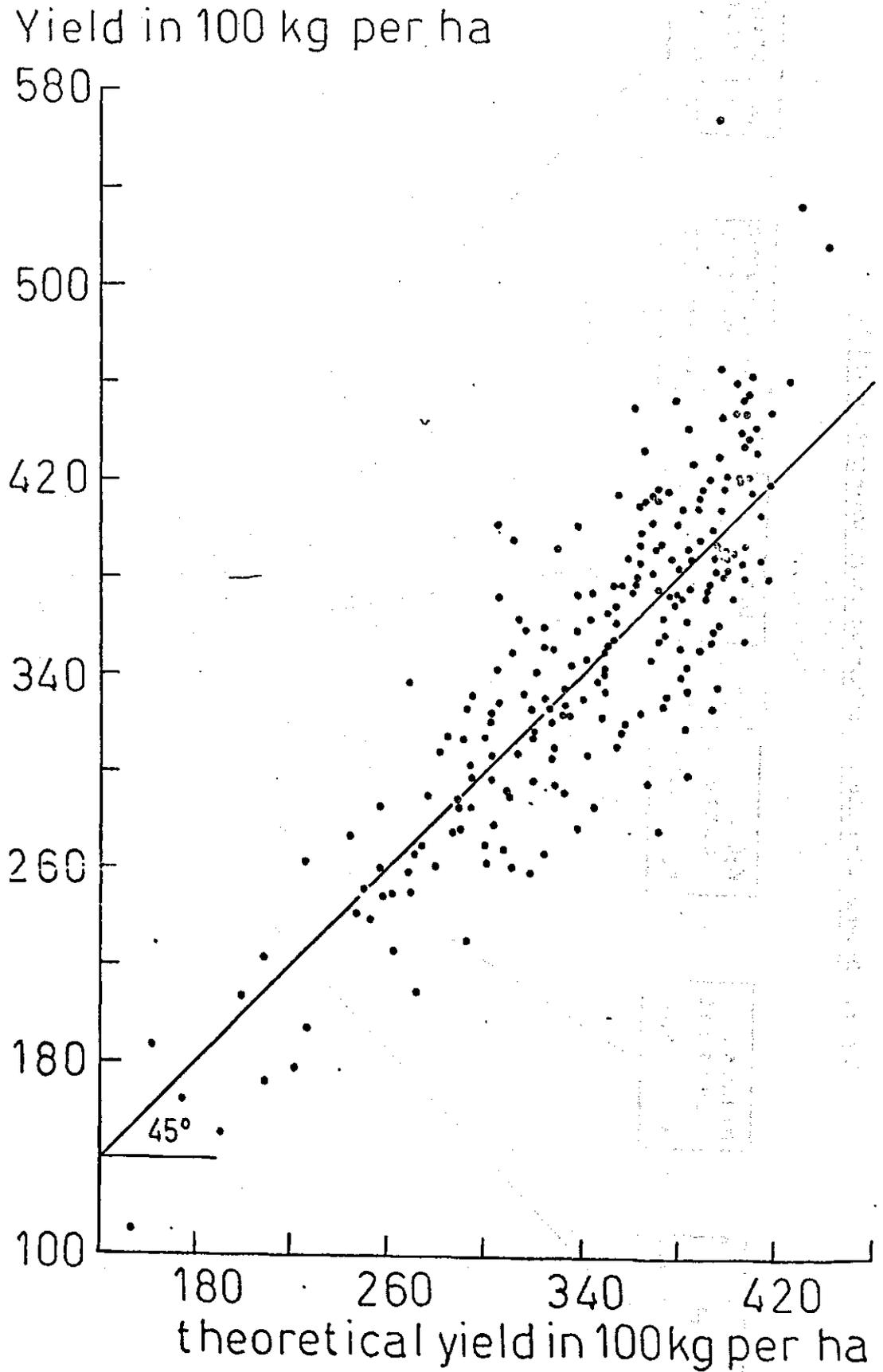


Fig. 6. Diagram with direct influences only; one-equation model.

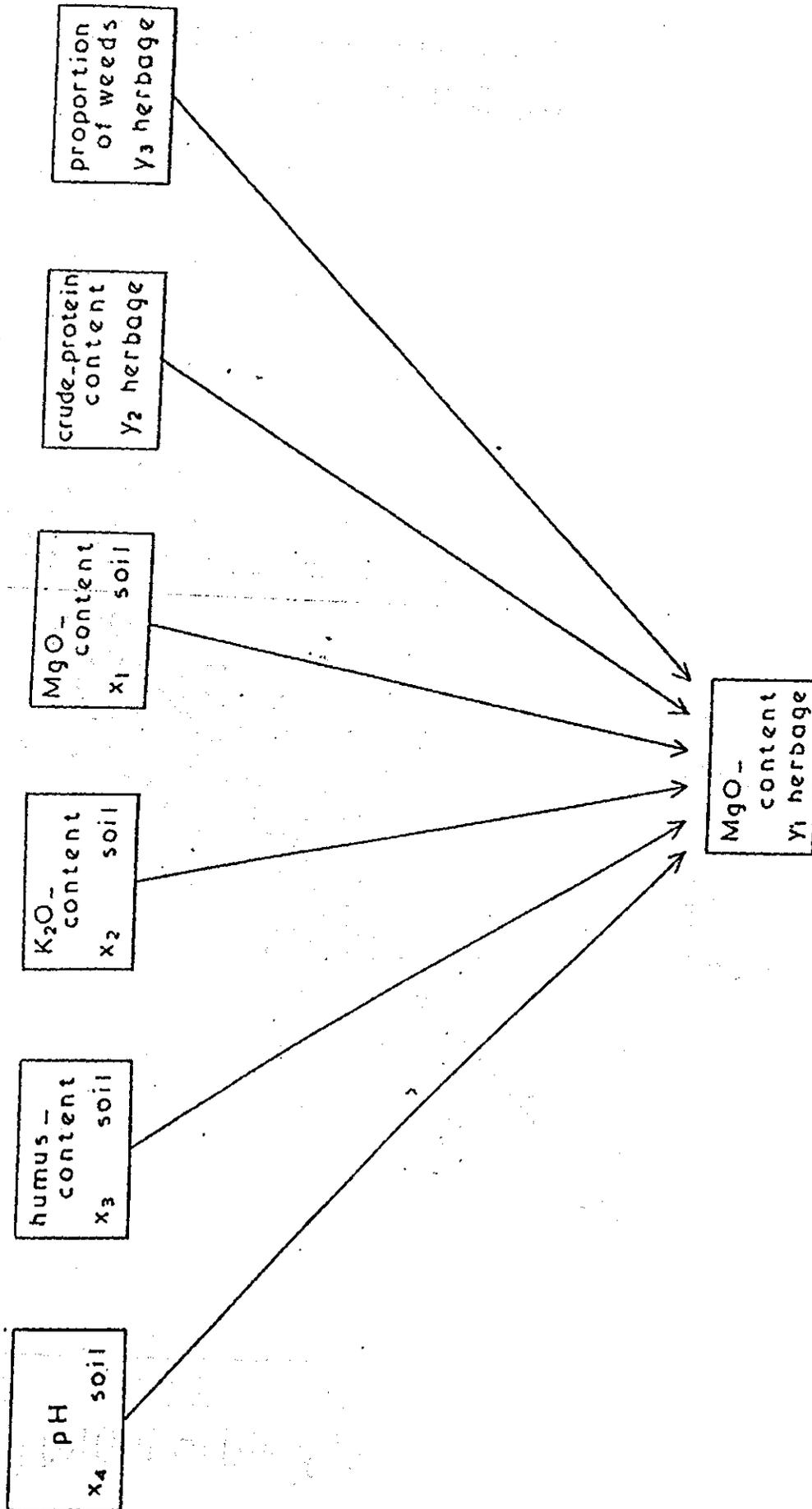


Fig. 7. Diagram with direct and indirect influences; more-equations model.

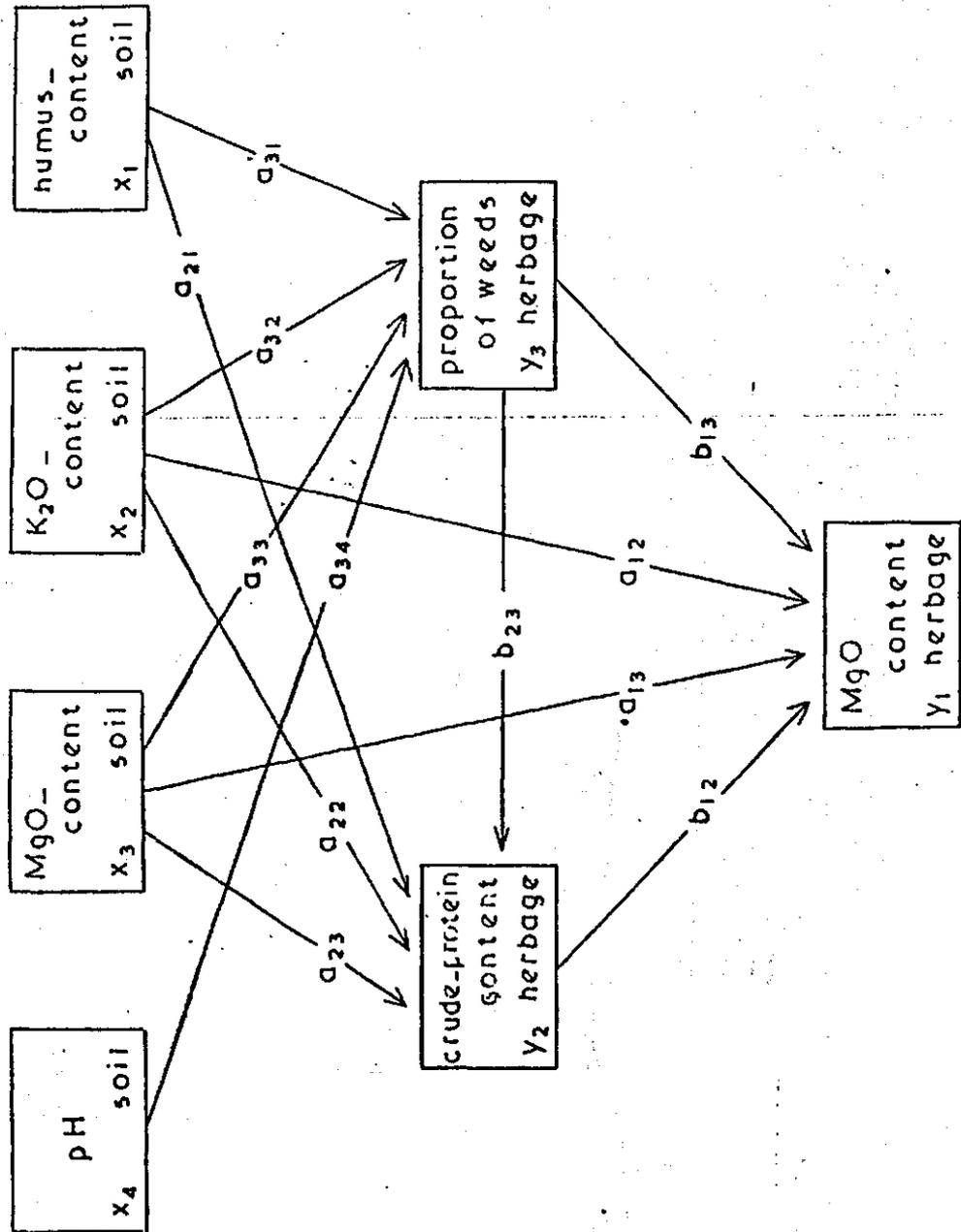


Figure 8. Experimental and simulated nitrate contents after 3 months in a sandy soil profile without groundwater. Dressing: 300 kilograms per ha.

