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MANURING, PLANT PRODUCTION AND THE CHEMICAL COMPOSITION OF THE PLANT

by F. STEENBJERG

Department of Soil Fertility and Plant Nutrition, The Royal Veterinary and Agricultural College, Copenhagen

When a crop is manured — manuring in the widest sense of the word and including for example light, temperature, humidity, *etc.* — the production of dry matter per unit area and the chemical composition of the dry matter are influenced. It is characteristic that both the total production and the various elements and compounds involved in this production are influenced. This means that the connection between the dry matter production, the production of protein, amino acids, vegetable oil, starch, sugar, fibres, absorption of various macro and micro elements, *etc.*, and the manuring is a rigid one in each special case.

The purpose of much work done during the last century has been to formulate general rules for the above-mentioned relationships. If such formulations are possible they may be used for various practical purposes.

The principal relationships may be expressed graphically, the units of the abscissa representing the amounts of manure added, the ordinate expressing the production of dry matter, and both values being expressed in terms of weight per unit area. All similar relationships which may be of interest are in one way or another derived from or related to this curve which will subsequently be called the yield curve. The yield curve may be extended to comprise coordinate systems with more than two axes.

THE VARIATION IN AND POSITION OF THE YIELD CURVE

The primary importance of the yield curve in all investigations of the above-mentioned kind has been appreciated at various times.

It is generally agreed to-day that mathematical expressions for the yield curve may be useful in a variety of ways. On the other hand knowledge of the fundamental factors influencing the yield curve cannot be obtained by mathematics, but only by well performed experiments, the design of which is in accordance with existing knowledge so that the results may throw further light on the yield curve and related matters. This may seem a superfluous statement, but it is justified by experiences which show that the design of many experiments and interpretation of the results of these experiments do not throw much light either on fundamental or on practical aspects of the problem, possibly because many of the investigations have been made for purely practical purposes.

When examining variations in the yield curve it is essential that determinations are made of the production of dry matter and the amount, or amounts, absorbed of those plant nutrients which are, or may become limiting — both expressed as quantities per unit area. — That such fundamental investigations must be made in this way is apparent from Figures 1, 2 and 3, in which the scale of the units of the abscissae and of the ordinates are the same in all three figures. These figures are more or less diagrammatic; details of the design of the experiments and the experimental results may be obtained from the following papers: Russel and Watson[15]), Hellriegel and Wilfarth[6]), Mitscherlich[12]), Wallace[26]) [27]) [28]) [29]), Kristensen[9]), Steenbjerg[17]) [18]) [19]) [20]) [21]) [22]) [23]) [24]), Poulsen[14]), Jacobsen[7]), Jakobsen[8]), Goodall and Gregory[3]), Brown and Harmer[2]), Haddock[4]) [5]), Boken[1]). These citations are made with particular reference to papers from this institute.

Figure 1 shows the relationship between the addition of increasing amounts of a plant nutrient, *t*, which is present in limiting quantities and the production of dry matter. Figure 2 shows the ratio between the amount added, *t*, and the amount absorbed, *o*, of this nutrient. The form of this curve may be altered by determination of coefficients of absorption of the nutrient in question by means of radioactive isotopes; this may alter some of the following conclusions with respect to the ease with which variation in the curve is observed, but will not alter the general shape of the yield curve in Fig. 3. Fig. 3 shows the relationship between the amount absorbed, *o*, of a plant nutrient present in limiting quantity and the production of dry matter. All yields, amounts of nutrients or amounts of nutrients added in Figs. 1, 2 and 3 are expressed in terms of weight per unit area. These three relationships are of fundamental importance.

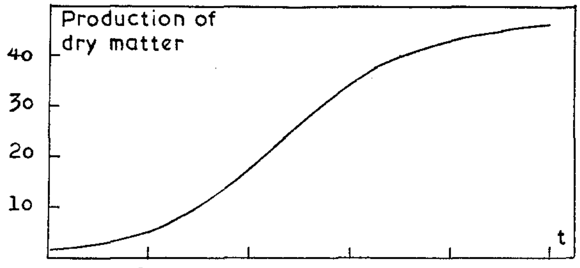

Fig. 1

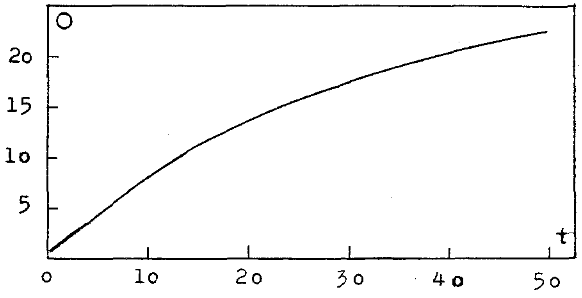

Fig. 2

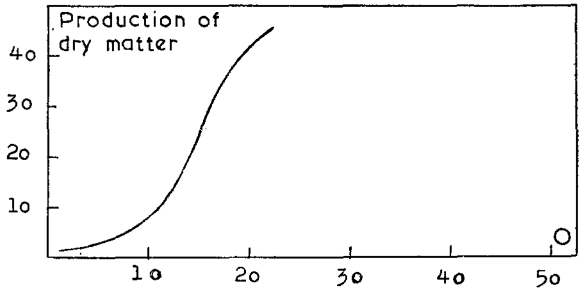

Fig. 3

Fig. 1. The relationship between *t* and the production of dry matter.
Fig. 2. The relationship between *t* and *o*.
Fig. 3. The relationship between *o* and the production of dry matter.

Fig. 3 is easily derived from Fig. 1; this has been done graphically through Fig. 2; the relationship represented in Fig. 2 may be determined by chemical methods.

The method of examining the form of the yield curve in Fig. 3 has two advantages, which so far seem to have been overlooked. The S-shape of the curve may be difficult to observe in Fig. 1, but as the coefficient of absorption falls with rising t-values it is evident that the concave part of the yield curve will be easier to observe in Fig. 3 than in Fig. 1. This method of investigating the shape of the curve has also the great advantage that one end of this yield curve coincides with the zero point of intersection of the axes. This point is therefore fixed and is extremely useful in the extrapolation and interpolation of experimental data for decreasing values of o and dry matter.

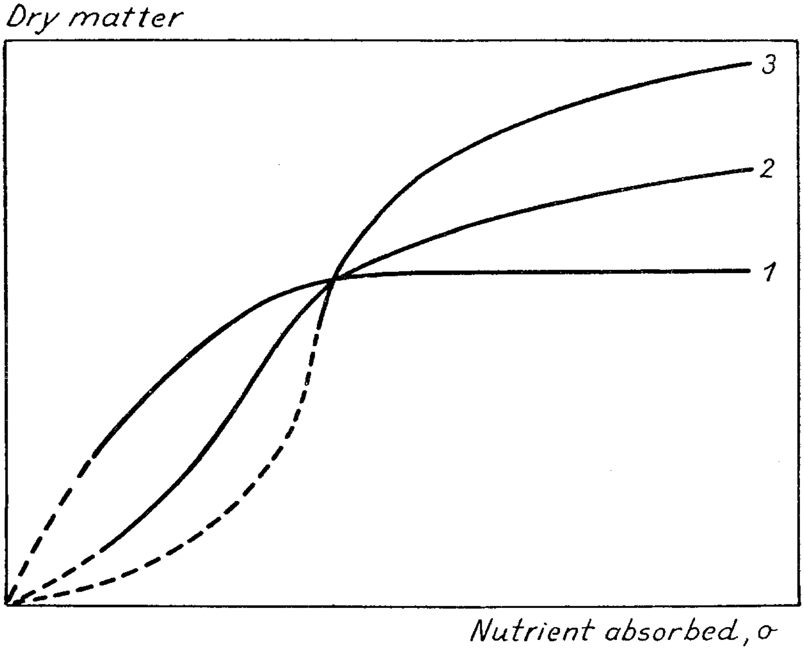

Fig. 4. The relationship between the amount of nutrient, present in limiting quantity, absorbed and the production of dry matter.

Fig. 4 shows a schematic graphic representation of a long series of experimental results mainly from this institute and from a few other papers, mainly Danish, where it has been possible to compute the amounts absorbed of the nutrient present in limiting quantity. The parts of the curves shown as an unbroken line are based on experimental results, while the parts of the curves shown as dotted lines represent interpolations to the zero point of intersection of the axes. The three types of yield curves (1, 2 and 3) in Fig. 4 must all have one end in, or very near, the zero point of the axes because production of dry matter without absorption of the plant nutrient present in limiting quantity as well as absorption of this nutrient without production of dry matter are equally inconceivable from a physiological point of view and, when apparently observed when the crop is harvested (because of observational errors), might give rise to strange deductions, indeed.

At present the following considerations seem useful when considering whether experiments have been carried out under conditions such that the S-shape of the yield curve may be observed; awareness of these criteria may be useful when smoothing the experimental results.

1. For the same plant, the lower the yield from the basic experimental treatment, the higher the probability of an S-shaped curve being observed.
2. If a very marked deficiency of the plant nutrient in question occurs in the basic treatment, then the amount of tissue imparting rigidity to the stem in gramineae generally seems to be very low, often so low that it may be detected by handling.
3. The observation of typical and widespread symptoms of deficiency of the plant nutrient present in limiting quantity in all replications receiving basic treatment make it probable that the curve should be S-shaped.
4. If the experimental results could be represented graphically as in Fig. 3, this would be very advantageous, as mentioned above.

For further details regarding the conditions governing the shape of the yield curve and its position in the coordinate system the following papers may be consulted: 17) 18) 19) 20) 21) 22) 23).

To prevent any misunderstanding it may be necessary to emphasize here that the S-shaped curve or parts of S-shaped curves have often been observed in well performed experiments concerning all the ordinary nutrients.

In what follows a few consequences of the S-shaped curve are considered; several more consequences easily present themselves, but will not be discussed here.

We shall first consider the results from two experiments, *1*) a field experiment with nitrogen (nitrate) in limiting quantity, and *2*) a pot experiment with copper in limiting quantity. The results from the experiment with nitrogen have been selected to show, among other things that even for a major nutrient, such as nitrogen, S-shaped curves may be observed when the results are obtained from a long term experiment where the soil, in the basic treatment and in one or two of the treatments where small amounts of nitrogen have been added, is more or less depleted of this nutrient.

In the field experiment (Fig. 5*a*) with nitrogen only the convex part of the yield curve is obtained; but it is clearly seen that the curve is actually S-shaped when the curve is extrapolated to the zero point of intersection of the axes. On the other hand, in the pot experiment, where copper is present in limiting quantity, nearly the whole of the yield curve is observed; and it is seen to be S-shaped. Figs. 5*a* and 6*a* show the relationship between the dry matter production per ha or per pot, and the amounts of nitrogen and copper absorbed, respectively. Figs. 5*b* and 6*b* show relationship between content of nitrogen (%), content of copper (ppm) and dry matter production.

Dry matter production plotted as the abscissa may be replaced by any other related factor, *e.g.* the corresponding amount of added nitrogen (when this is a limiting factor), starch production, vegetable oil production, protein production, or whatever factor is of interest. It may be added here that if the slope of the yield curve in question decreases when very large amounts of the nutrient present in limiting quantity are added (increasing negative increments of *e.g.* dry matter), then the case is further complicated and will not be considered here.

Some of the consequences of these observations of S-shaped curves or parts of curves, which are essentially parts of S-shaped curves, are exemplified in Figs. 5*a*, 6*a*, 5*b*, and 6*b*. The first example is chosen because it shows how important it is to consider both the possible shape of the yield curve, which so far has been discussed most in the present paper, and its position in the coordinate system. The use of chemical analyses of nutrient elements in plants or parts of plants as an index of the nutritional status of these plants has been much advocated in recent years. The purpose of such analyses is to make possible recommendations regarding manurial treatments

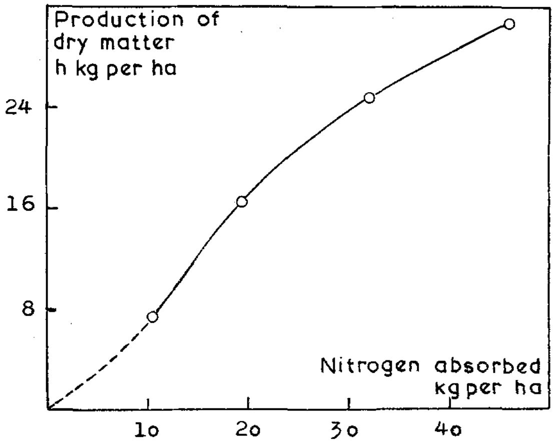

Fig.5a

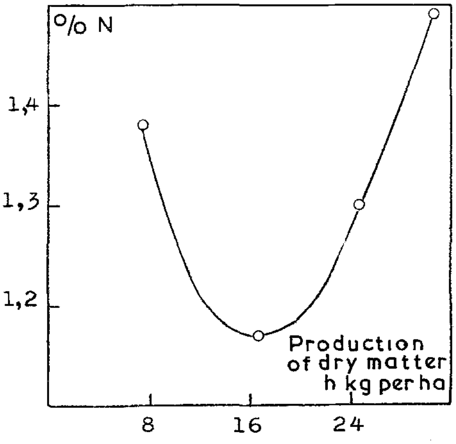

Fig.5b

Fig. 5*a*. The relationship between nitrogen absorbed and the production of dry matter. Timothy. Leaves + straw. — Tylstrup 1931–42.

Fig. 5*b*. The relationship between the production of dry matter and the content of nitrogen as a percentage of the dry matter. Timothy. Leaves + straw. — Tylstrup 1931–42.

on either a qualitative or a quantitative basis. These recommendations may be derived from appropriate field experiments the results of which are analysed statistically, primarily with respect to the

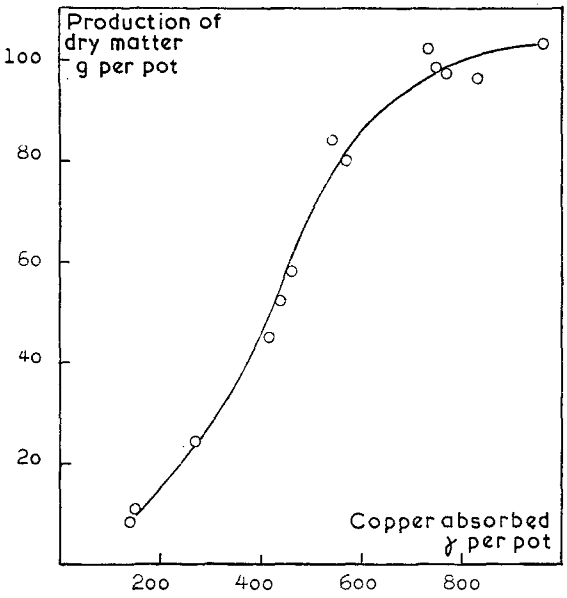

Fig. 6a

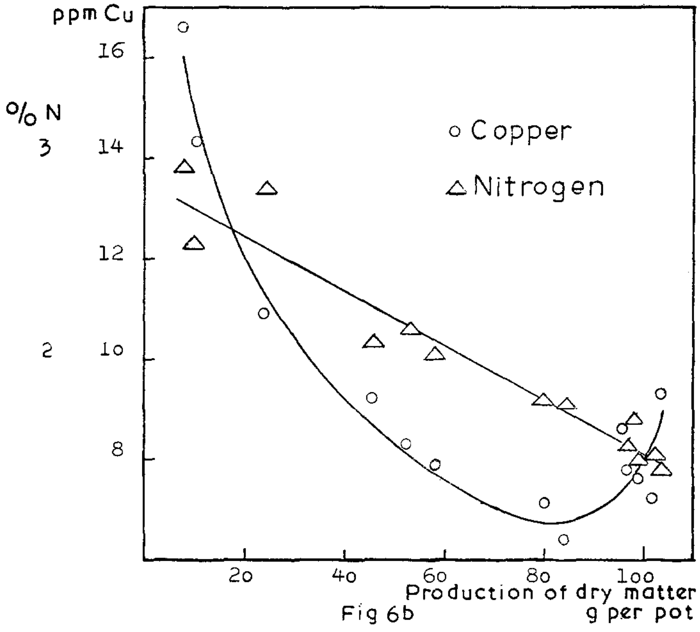

Fig 6b

Fig. 6*a*. The relationship between copper absorbed and the production of dry matter. Barley. Leaves + straw. — Copenhagen, 1939–41.

Fig. 6*b*. The relationship between the production of dry matter and the relative content of copper (ppm) and nitrogen (%). Dry matter basis. Barley. Leaves + straw. — Copenhagen 1939–41.

nutrient present in limiting concentration, but also with regard to other factors of production, which are most important in connection with the form and position of the yield curve [23]). A special method of statistical treatment (verification) is met with in the so called spot or patch investigation, a method of special value in all cases in which few results from field experiments are available for verification of the results of the chemical analyses. At least three samples of plant material (the whole plant or parts of it according to preceding investigations) are taken from healthy, less healthy, and deficient crops (Figs. 5*a* and 6*a*), and the contents of the most important plant nutrients are determined.

When taking samples of material for analyses care must be taken to choose such organs of the plants (or the whole plants) that the differences in the analytical results will be as great as possible. The same care is necessary when choosing analytical methods and agents used for extraction. The determination of the total percentage content of a nutrient in the dry matter — and this must be considered the standard method — may be used to obtain this maximum variation, while in the case of a few elements, such as for example nitrogen, fractionation into the various forms such as total nitrogen and nitrate nitrogen *etc.*, may often be used with advantage (Ulrich [25]), Haddock [4]) [5])). However, very few results are available which allow of a comparison between the values of these fractions and the values of total contents (Jacobsen [7])). Finally, the sampling should be carried out during that part of the growing season when differences in the analytical results will be greatest; in temperate climates this means the early summer, *i.e.* May and June. In this connection it is suggestive that the most pronounced and widespread symptoms of deficiency are generally found in the above-mentioned early periods of growth.

The interpretation of the results when using this method of sampling is based on the assumption that by sampling simultaneously and with as small distances as possible all factors influencing the shape and position of the yield curve, except the one limiting growth, are kept constant or as nearly so as possible at the places of sampling. This means that when sampling, distances in time and space must necessarily be very small. It is of vital importance that this elimination of variables be successfully carried out when sampling, as otherwise one may inadvertently measure simultaneously the influence of two or more factors on the yield curve and on the percentage content of for example one of the nutrient elements. How complicated and how difficult the interpretation may be in apparently rather simple cases is exemplified in the diagrams in Figs. 7*a* and 7*b*; here more than one factor of production has been varied simultaneously in the three sampling sites for both the first and the second sampling.

By simultaneous sampling on patches separated by distances as small as possible one ensures, as far as possible, that the varying yields corresponding to the samples taken, originate from one yield curve and not from three curves as in Fig. 7*a*. This simplifies the interpretation of the results originating from spot investigations because one only needs to pay special attention to the shape of the yield curve; but even in this case the interpretation may be difficult. It is important that a series of measurements is secured, the graphic representation of which resembles Figs. 5*b* and 6*b*. Furthermore, it is necessary to analyse the plant samples for several elements, not only the one which may be in limiting quantity. When present in sufficient quantities the percentage contents of the nutrients not present in limiting concentration will, on the whole, show a constant decrease with increasing weight of dry matter of the crop. On the other hand, the nutrient present in limiting concentration shows first a decrease and then an increase in percentage content with increasing amount of dry-matter production. If samples of such crops are obtained for chemical analysis, the information on the yield and the appearance of deficiency symptoms may be lacking or inaccurate; hence it may be necessary to analyse the crop not only for the plant nutrient present in limiting concentration but also for a number of other plant nutrients (Fig. 6*b*).

On the whole it seems necessary to use chemical analyses of plant material with caution and some reservation as a diagnostic criterion of deficiency of soils and crops in plant nutrients. Such analyses should never be used alone, but always in conjunction with other independent methods of observation (compare Lundegårdh 10) 11)).

The second example shows some other consequences of the S-shaped yield curve; it is chosen because it demonstrates how careful one must be when selecting plant material for chemical analyses with respect to percentage content of various important constituents in the crop on a dry-matter basis. In the experiment with nitrogen (Fig. 5*b*) it is seen that the percentage content of crude protein may be exactly the same in two crops which are very differ-

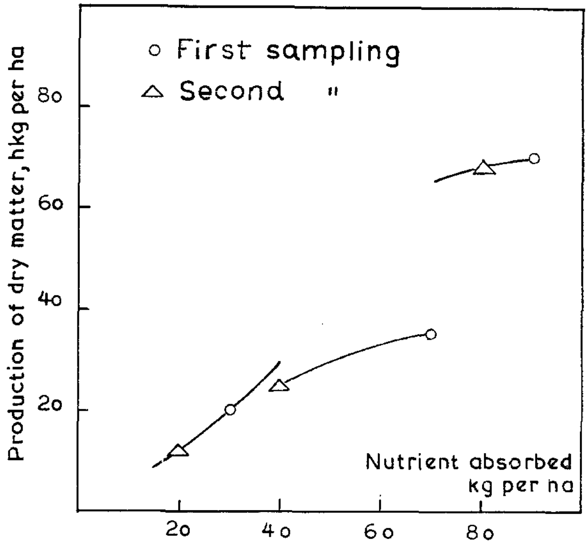

Fig. 7a

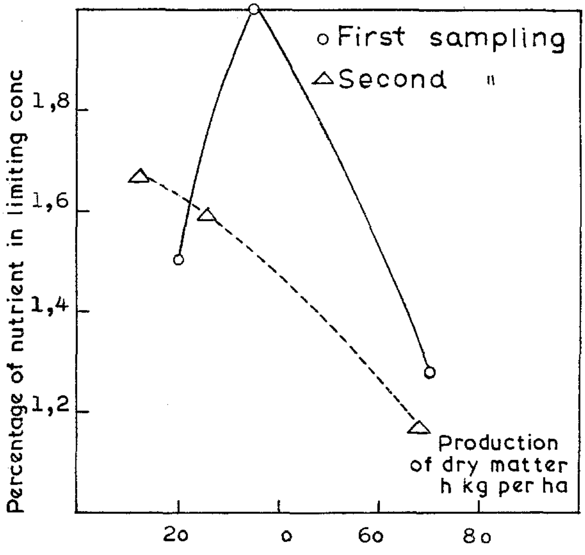

Fig. 7b

Fig. 7*a*. The relationship between the nutrient absorbed (present in limiting concentration under various circumstances with respect to other nutrients) and the production of dry matter.

Fig. 7*b*. The relationship between the production of dry matter and the percentage content of the nutrient present in limiting concentration (under various circumstances with respect to other nutrients).

ent in the amount of dry matter produced. Thus in a field experiment in which increasing amounts of nitrogen are added to the soil, and the experiment includes only a few experimental treatments, one may by accident sample crops which show no variation or only a very small variation in the percentage content of crude protein with increasing addition of nitrogen to the soil and increasing crop production; one may even find decreasing nitrogen content with increasing nitrogen addition to the soil.

The same picture of the influence of nitrogen fertilisation may be obtained for other nitrogenous compounds found in the plant. Therefore, when using plant material for chemical analysis from long-term field experiments in which the soil in the basic treatment is generally more or less depleted of nitrogen, one must be careful. Many surprisingly small variations of the above-mentioned kind may have been caused by an underlying S-shaped yield curve for dry-matter production.

In this connection it should be mentioned that the computed yield curve for crude protein is S-shaped when calculated on the basis of Fig. 5*a* and Fig. 5*b*, but the very same is true of the yield curve for crude protein (Fig. 8) when computed on the basis of Fig. 6*a* and Fig. 6*b*. These facts are rather important and open up new fields for further research.

Furthermore, the above-mentioned facts mean, among other things that proportions of percentage contents, *e.g.* $\frac{\text{ppm Cu}}{\%\ \text{N}}$ or $\frac{\%\ \text{N}}{\%\ \text{P}}$, *etc.* in the above-mentioned examples are of small importance for the verification of chemical plant analyses or tissue tests.

The third example is chosen to show that the shape and position of the yield curve is most important in determining the most beneficial distribution of a given amount of a nutrient element which is present in limiting concentration on a given area. The most beneficial distribution is defined as that which for a given amount of a fertilizer, gives the highest yield per unit area.

When trying to determine which method of distribution is most beneficial it must be remembered that several experiments with different plant nutrients in various parts of the world have shown that uneven distribution of fertilizers, *e.g.* in rows, or otherwise have in some cases given enormously higher yields than an even distribution on the surface of the soil. The causes are different in different cases and in fact are not known precisely.

The explanation may lie in the fact that some soils, often, but not always, soils depleted of the nutrient in question, have a very high fixing power for the nutrient, making it difficult for the plants to absorb it. This may be one of the causes of the concave part of the yield curve.

In such cases, instead of choosing an uneven distribution of a given amount of the nutrient on a given area of soil, the fertilizer, if watersoluble, may — as shown by much research work — with great economy of material be sprayed in small concentrations on the leaves, twigs, branches, *etc.*, of the plants once or several times during the growing period or at other times of the year.

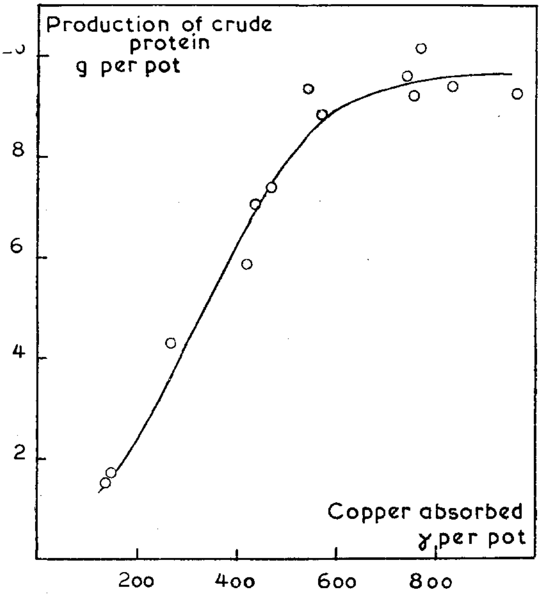

Fig. 8. The relationship between the copper absorbed and the production of crude protein. Barley. Leaves + straw. — Copenhagen 1939–41.

The consideration governing the choice of an uneven distribution of a given amount of nutrient to the soil seems to be that the underlying yield curve represents the lower part of the curve, part of which is concave.

Under many conditions, however, it may often pay to manure in such a way that the yield level lies on the upper part of the curve. This means that more nutrient must be brought into circulation in the field when conditions of production allow this. In this connection it should also be remembered that an uneven distribution does not last in a soil which is ploughed, *etc.*, at regular intervals.

Simple considerations will show:

1. That when a given amount of the fertilizer in question is broadcast and distributed as evenly as possible on a given unit of area, *e.g.* 1 ha, any other distribution of the same amount of fertilizer on the same area will provide exactly the same yield per ha if the yield curve is a straight line.

2. That when a given amount of the fertilizer in question is broadcast and distributed as evenly as possible on a unit area *e.g.* 1 ha, the highest yield will be obtained from this kind of distribution when the underlying part of the yield curve is convex.

3. When forced to work on the lower part of the yield curve part of which is concave, the highest yield will be obtained by an uneven distribution. The degree of unevenness of distribution depends on the shape and position of the yield curve.

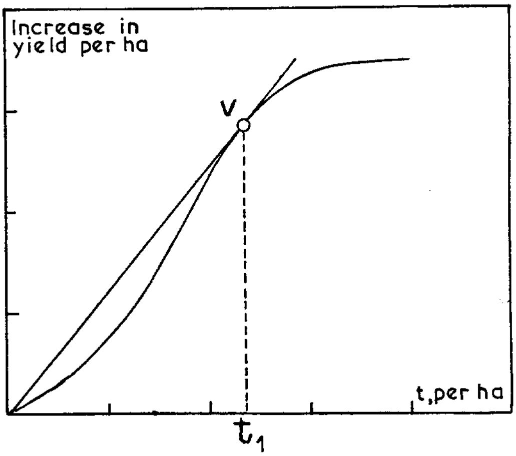

Fig. 9. The relationship between the nutrient added, *t* and the increase in yield.

In Fig. 9 is a diagrammatic representation which shows a tangent at the point, *v*, extended through the zero point of intersection of the coordinate axes. The reciprocal t_1-value in Fig. 9 gives that part of 1 ha on which one unit of a fertilizer must be spread evenly in order that the highest yield is obtained per ha (compare de Wit [31]). Instead of absolute values relative values for fertilizers may be used.

An example illustrating this is given below: An experiment in which increasing amounts of a fertilizer have been used has been performed, and the fertilizer in question has been spread as evenly as possible. Table I gives the results:

TABLE I

Units of fertilizers added/ha	Total increase in yield/ha	Yield increments	Increase in yield per unit of fertilizer/ha
1	1.5	1.5	1.50
2	4.0	2.5	2.00
3	8.0	**4.0**	2.67
4	11.7	3.7	**2.93**
5	14.2	2.5	2.84
6	15.9	1.7	2.65

The largest increase in yield per unit of fertilizer per ha is obtained on addition of 4 units of fertilizer per ha. If only 1 unit of the fertilizer is available for use the largest increase in yield per ha will be obtained by spreading it on $^1/_4$ of a ha; if 2 units of a fertilizer are obtainable they should be spread on the half of 1 ha and spread as evenly as possible on this half ha as mentioned above. If more than 4 units of the fertilizer are available per ha the fertilizer should be spread as evenly as possible over the whole of the area.

The increase in yield per unit of fertilizer per ha is equal to the average value of the preceeding yield increments *e.g.* for 4 units of the fertilizer: $1.5 + 2.5 + 4.0 + 3.7 = 11.7$, $11.7 : 4 = 2.93$. This is the reason for the maximum increase in yield per unit of the fertilizer per ha not coinciding completely with the maximum yield increment which in this example is found when 3 units of the fertilizer are applied per ha and which marks the point of inflexion of the curve.

As long as the yield increment is larger than the average value of the preceeding yield increments the increase in yield per unit of the fertilizer per ha increases and vice versa.

An uneven distribution of a fertilizer is dictated by the necessity for working on the lower part of the yield curve — for economical reasons and/or lack of the necessary fertilizers in such amounts as would raise the yield to that point of the curve where the highest net result may ordinarily be obtained.

SUMMARY

The paper deals with some of the consequences of an S-shaped yield curve with special reference 1) to the chemical composition of the plant and 2) to the distribution of fertilizers.

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LITERATURE

1) Boken, E., Unpublished data on manganese (1952).

2) Brown, John C. and Harmer, Paul M., The influence of copper compounds on the yield, growth pattern, and composition of spring wheat and corn grown on organic soil. Soil Sci. Amer. Proc. **15**, 284 (1950).

3) Goodall, D. W. and Gregory, F. G., Chemical composition of plants as an index of their nutritional status. Imp. Bur. Hort. Plantation Crops. — Tech. Commun. 17 (1947).
4) Haddock, Jay L., Nutritional status of sugar beet as revealed by chemical analyses of petioles. Proc. Am. Soc. Sugar Beet Technol. p. 334 (1950).
5) Haddock, Jay L., Sugar beet yield and quality. Agric. Exp. Sta. Utah State Agr. Coll. Bull. p. 362 (1953).
6) Hellriegel, H. and Wilfarth, H., Untersuchungen über die Stickstoffnahrung der Gramineen und Leguminosen. Deut. Zuckerind. **XIV** Nr. 1, Spalte 4 (1889).
7) Jacobsen, Ingeborg, Om planternes manganindhold som hjælpemiddel ved bestemmelse af manganmangel (English summary) Horticultura Nr. 10, 89 (1951).
8) Jakobsen, Svend T., Om den S-formede udbyttekurves betydning for vurderingen af den kemiske planteanalyse, (English summary). Horticultura Nr. 2, 12 (1952).
9) Kristensen, R. K., Danske Afgrødeanalyser. Tidsskr. Planteavl **43**, 830 (1939).
10) Lundegårdh, H., The triple analysis method of testing soil fertility and probable crop reaction to fertilization. Soil Sci. **45**, 447 (1938).
11) Lundegårdh, H., Leaf analysis. Hilger & Watts Ltd., Hilger Division. London (1951).
12) Mitscherlich, E. A., Om Vækstfaktorernes Virkningslov. Nord. Jordbrugsforskn. 1922, Nr. 1, 161 (1922).
13) Nicholas, D. J. D. ,A survey of the use of chemical tissue tests for determining the mineral status of crop plants. Soils and Fertilizers, **XIV**, 191 (1951).
14) Poulsen, J. F., Studier over forskellige Fosfaters Gødningsværdi. Om Stofproduktionen og Optagelsen af Fosfor fra forskellige Fosforgødninger. III (Studies on the fertilizing value of different phosphates. On the production of dry matter and the absorption of phosphorus from different phosphate fertilizers. III). Tidsskr. Planteavl **53**, 413 (1950).
15) Russel, E. J. and Watson D. J., The Rothamsted field experiments on the growth of wheat. Imp. Bur. Soil Sci. Techn. Commun. **40** (1940).
16) Sideris, C. P., Young, H. Y. and Krauss, B. H., Effects of Iron on the growth and ash constituents of *Ananas comosus* (L) Merr. Plant Physiol. **18**, 608 (1943).
17) Steenbjerg, F., Kobber i Jord og Kulturplanter. Med særligt Henblik paa Gulspidssyge. (Copper in soils and cultivated plants. With special reference to white-tip disease). Tidsskr. Planteavl **47**, 259 (1941).
18) Steenbjerg, F., Kobber i Jord og Kulturplanter. II. Undersøgelser over Kobbermineralers Gødningsværdi. (Copper in soils and cultivated plants. II. Investigations on the fertilizing value of copper minerals.) With a summary in English. Tidsskr. Planteavl **47**, 557 (1943).
19) Steenbjerg, F., Om kemiske Planteanalyser og deres Anvendelse (On chemical analyses of plants and their use). With a summary in English. Tidsskr. Planteavl **49**, 158 (1945).
20) Steenbjerg, F., Investigations on micro elements from a practical point of view. Trace Elements in Plant Physiology **3**, 87. Waltham, Mass. U.S.A. (1950).
21) Steenbjerg, F., Yield curves and chemical plant analyses. Plant and Soil **III**, 97 (1951).
22) Steenbjerg, F., On the relative contents of plant nutrients in crops. Trans. Intern. Congr. Soil Sci. (Amsterdam) **I** (1950).
23) Steenbjerg, F., Verification of chemical soil and plant analyses: General considerations. Intern. Soc. Soil Sci. Transactions of the joint meeting of Commission II and Commission IV (Dublin) **I**, 309 (1952).

24) Steenbjerg, F., Unpublished data.
25) Ulrich, A., Plant analysis as a diagnostic procedure. Soil Sci. **55**, 101 (1943).
26) Wallace, T. and Mann, C. E. T., Investigations on chlorosis of fruit trees. I. The composition of apple leaves in cases of lime-induced chlorosis. J. Pomol. **5**, 115 (1926).
27) Wallace, T., The effects of manurial treatments on the chemical composition of gooseberry bushes. I. Effects on dry matter ash and ash constituents of leaves and stems of terminal shoots and of fruits; and on total nitrogen of fruits. J. Pomol. **7**, 130 (1928).
28) Wallace, T., Experiments on the manuring of fruit trees, III. The effects of deficiencies of potassium, calcium and magnesium, respectively, on the contents of these elements, and of phosphorus in the shoot and trunk regions of apple trees. J. Pomol. **8**, 23 (1929). Abridged in Rep. Agric. Hort. Research Sta. Bristol for 1929, 47.
29) Wallace, T. and Proebsting, E. L., The potassium status of soils and fruit plants in some cases of potassium deficiency. J. Pomol. **11**, 120 (1933).
30) Wallace, T., Plant diagnostic methods. Intern. Soc. Soil Sci. Transactions of the joint meeting of Commission II and Commission IV (Dublin) **I**, 231 (1952).
31) Wit, C. T. de, A physical theory on placement of fertilizers. Dissertation, Wageningen (1953).