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PERIODIC FLUCTUATIONS OF SOIL FERTILITY, CROP YIELDS AND OF RESPONSES TO FERTILIZATION EFFECTED BY ALTERNATING PERIODS OF LOW OR HIGH RAINFALL

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1. INTRODUCTION

Meteorological literature is full of periodic phenomena. Shaw [23] in 1927 compiled a list of 131 empirical periods of one year or more derived from the examination of long series of observations. Concerning the origin of periodicities Berlage [2] jokingly remarks: "Hydrosphere and atmosphere are perpetually cooking on the solar fire a long periodic meal".

Air pressure is regarded as being a primary factor in this process but temperature and precipitation are secondarily involved. From the agronomical point of view the latter is probably of greatest importance.

The periodicities observed are not generally strict but the rather irregular waves have different lengths of period. As Berlage points out ... "everyone who is acquainted with 'periodicities' of this kind knows that the cyclic processes in the physical sense which might explain such phenomena, are never strictly periodic".

Biological periodicities of a similar kind have been attributed to meteorological fluctuations. Cyclic wood growth has been studied by Kapteyn [12] and Douglass [6 7] who analysed the sequence of annual rings in Sequoia. Huntington [10] has correlated the latter with climatic changes which might have promoted the repeated rise and decline of Maya civilisations. A statistical analysis of wheat prices in England from 1545 to 1844 led Beveridge [3] to assume many periodicities of wheat yields with periods varying between

2.735 and 68.0 years. Some of these periodicities have by this author been identified with well-known meteorological cycles and it may follow that the sequence of wheat yields has depended on periodicities of rainfall. Kamerling[11] first drew attention to periodic fluctuations in crop yield. Bean[1] and van der Paauw[14 15] supplied further evidence suggesting that the phenomena are due to meteorological causes. A new conception was presented at the Seventh International Congress of Soil Science at Madison, Wisconsin, U.S.A.[19].

In the present paper special attention will be paid to the effect of "cyclic" rainfall periods on the fertility of the soil. An attempt will be made to show that periodic trends of some major fertility factors are induced by the fairly regular alternation of periods of different rainfall. Corresponding cyclic fluctuations of crop yield and of crop response to fertilization treatments will be ascribed to those periodicities of soil fertility.

2. ALTERNATING PERIODS OF DIFFERENT RAINFALL

A "periodicity" in rainfall in the sense described above seems to be apparent in the last half century. This is demonstrated by a summation curve of the deviations of average monthly precipitation * of the period 1–1–1880 to 1-7–1961 (Fig. 1). The summation curve is used for a comparison between rate of rainfall and agricultural data because it clearly demonstrates the rather sudden changes from a period with rainfall of a distinct level to one with a different level. Within such a period the rainfall is relatively constant (Fig. 2). Apart from apparent fluctuations of minor importance a rather regular alternation of persistent type of wheather in which precipitation is quite different from that of preceding and following ones is clear from about 1910 onwards. Rising parts of the curve indicate periods with a rainfall below the average and vice versa. The duration of these periods often amounted to approximately 1½ to 3 year and that of a whole "cycle" to about 3 to 6 years.

* A summation curve is obtained either by making use of the deviations from monthly rainfall (one twelfth of the average annual rainfall), or by applying those from the averages of each month separately. In the latter case average seasonal fluctuations are eliminated. Both methods are used depending on circumstances. In Fig. 1 the averages of each month separately have been calculated for period 1-1-1880 to 31-12-1958.

It must be noticed, however, that the phenomenon is not regular in the sense that dry and wet periods always alternate. Between

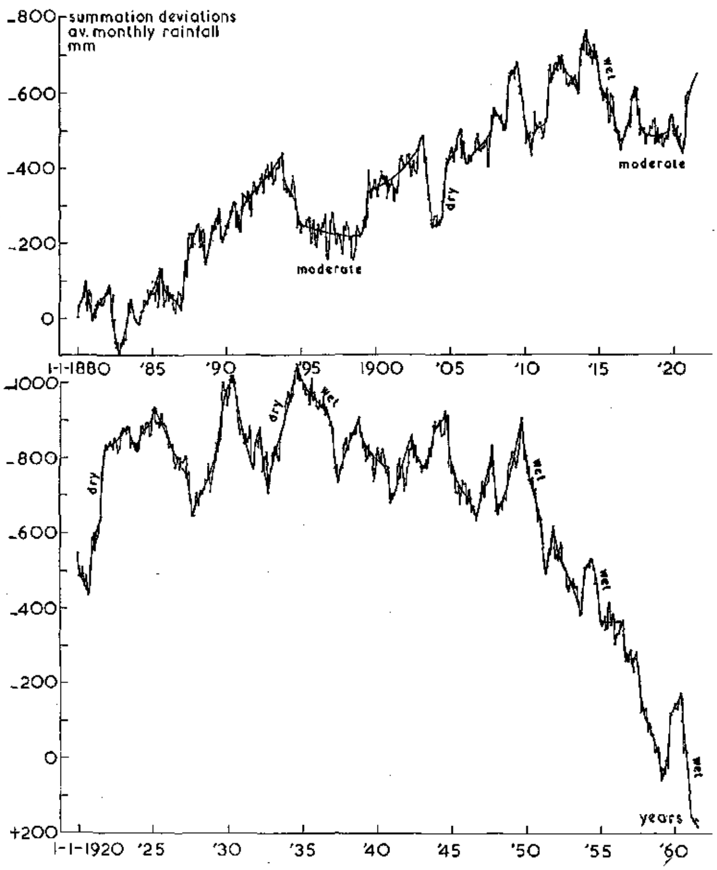

Fig. 1. Summation curve of deviations from average monthly rainfall (averages calculated for each month separately, in 1880–1958) at Groningen in the period 1 Jan. 1880–1 Juli 1961.

the years 1914 and 1927 the very wet period of 1914 to 1916 was followed by one of moderate rainfall which in its turn gave place to a very dry one. After 1922 there was again a period of moderate rainfall followed by the wet period of 1925 to 1927.

The differences between the average precipitations in these periods are appreciable. For instance, the average monthly rainfall in the dry periods of 1920–1921, 1927–1930 and 1932–1934 amounted to 35.6, 48.2 and 44.6 mm and in the wet ones of 1925–1927, 1930–1932 and 1934–1937 to 71.0, 70.7 and 70.2 mm respectively. Since

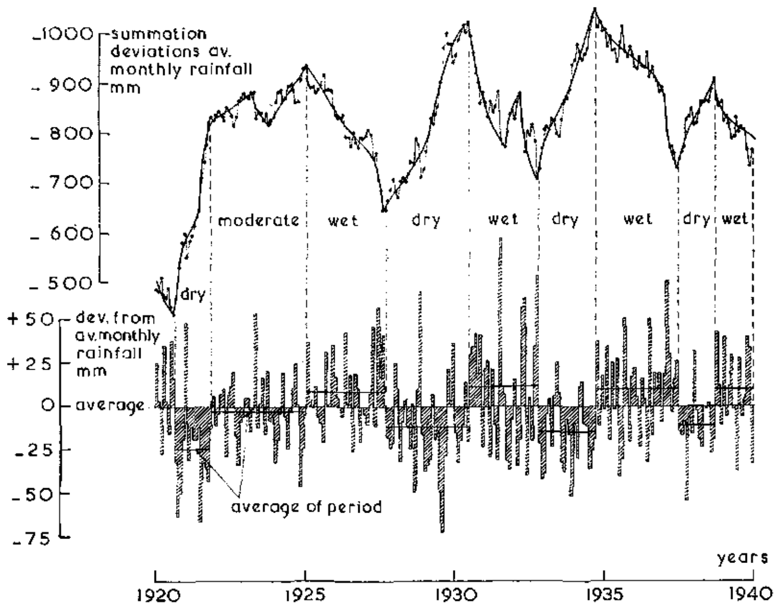

Fig. 2. Deviations from average monthly rainfall in 1920–1940 (below) and summation curve of same (above). The sudden changes from periods with distinctly different levels of rainfall are spectacularly demonstrated by the upper curve.

1949 rainfall has increased markedly. From 1950 to 1959 the monthly average amounted to 67.5 mm against 58.5 mm from 1880 to 1950. Owing to the sharp fall in the curve since 1949 the occurrence of a periodicity is less clear in Fig. 1. A summation curve for the period 1946 to 1961 (Fig. 14) clearly demonstrates that the alternation of rainfall periods has persisted until the present.

A similar alternation of wet and dry periods could also be demonstrated between 1850 and 1880 in England (Fig. 11).

3. CUMULATIVE EFFECT OF RAINFALL PERIODS ON SOIL-FERTILITY FACTORS

A close correspondence between the cumulative excess of rainfall and the trends of some soil-fertility factors will be demonstrated.

a. *Effect of alternating periods of different rainfall on pH of the soil*

The pH in water suspension was determined bimonthly on the experimental field Pr 837 on humic sandy soil. The trend of pH corresponds fairly closely to alternating wet and dry periods as shown by a summation curve of the deviations of average half-monthly rainfall in the period 1946–1952 (Fig. 3). It gradually

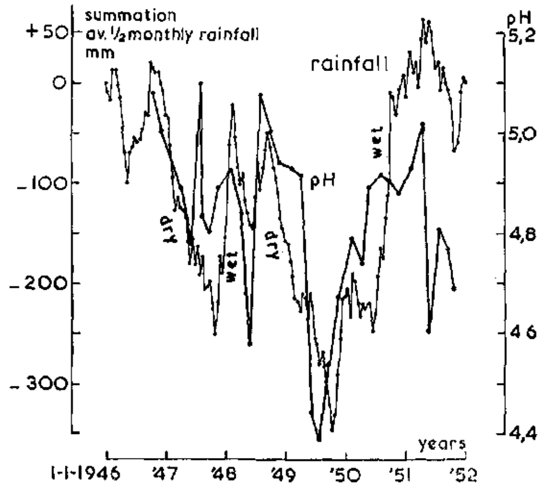

Fig. 3. Time course of pH compared with summation curve of deviations from average half-monthly rainfall (1/24 part of yearly average) at Groningen for the period 1946–1952 at exp. field Pr 837.

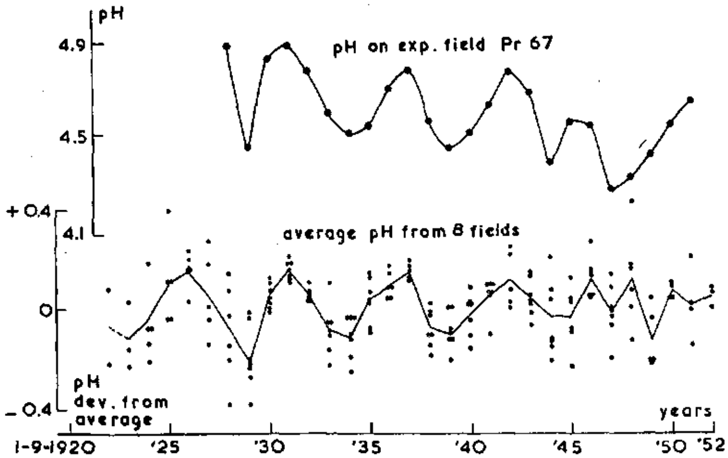

Fig. 4. Periodic fluctuations of pH(H_2O) at exp.field Pr 67 and average trend of pH of 8 long-term experimental fields (below).

increases in periods of high and decreases in periods of low rainfall.

The regular alternation of periods of different rainfall between 1921 to 1952 has obviously given rise to a remarkable, undulating trend of pH on long-term experimental fields (Fig. 4). The gently upper curve is based upon the average (of 6 replicates analysed in duplicate) pH determined at harvest on the experimental field Pr 67 on humic sandy soil. The variation of average pH on 8 long-term experimental fields on humic sandy soils (including Pr 67) found after elimination of linear long-term trends is similar (lower curve). The slight scatter of dots in some years (*e.g.* 1930–1932) shows that the agreement between the results of different fields was close.

Generally a gradual rise of the pH-curve occurs in wet periods and a fall in dry ones (Fig. 10).

b. *Effect of alternating periods of different rainfall on the content of water-soluble phosphorus in the soil*

The trend of average content of water-soluble phosphorus * determined bimonthly over a period of six years on seven experimental fields corresponds in general to the alternations of rainfall in this period (Fig. 5). Unlike pH the phosphorus content gradually rises in the dry period 1948–1950 and falls in the wet period 1950–1952. The picture is irregular at first, especially the second observation. Fluctuations are due to fertilization, uptake and errors.

Another case where the periodic variation of the content of water-soluble phosphorus closely corresponds to the alternation of periods of different rainfall is shown in Fig. 13.

Similar though relatively smaller fluctuations in the content of 1% citric acid-soluble phosphorus have also been found (Fig. 5). On some experimental fields the total amount of soil phosphorus extracted with Fleischmann acid (a mixture of equal parts of strong sulphuric acid and nitric acid) has also been determined. In this case similar trends though less pronounced have been observed. For instance from 7–2–1950 till 22–10–1951 (a wet period) the content of water-soluble phosphorus decreased from 13.9 to 9.7 (averages) in the experimental field Pr 836. In the same period the amount of total phosphorus fell from 148 to 135. The decrease in

* Extraction of 1 part of soil by 10 parts of water at 50°C during 24 hours. Amount of phosphorus expressed as in mg P_2O_5/100 g of soil.

the content of water-soluble phosphorus thus amounted to 30 per cent, that of total phosphorus to 9 per cent so that the ratio soluble

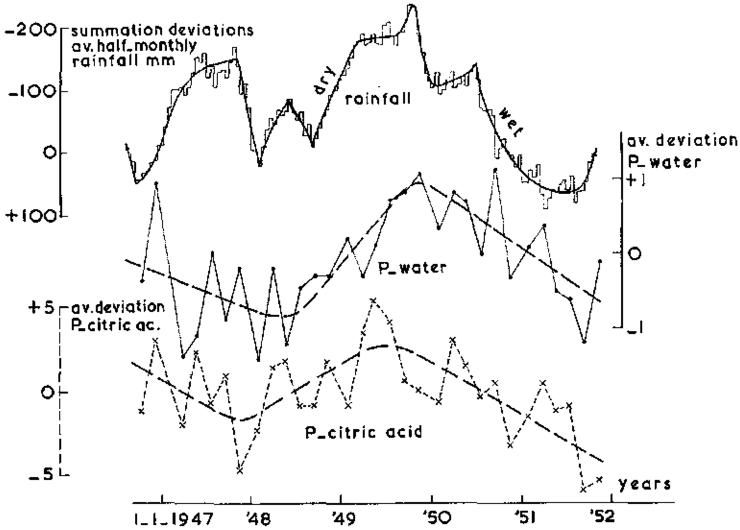

Fig. 5. Average trends of contents of phosphorus soluble in water and in citric acid at 7 experimental fields compared with summation curve of deviations from average half-monthly rainfall (1/24 part of yearly average) at Veendam in period 1 Sept. 1946–31 Oct. 1951.

P/total P has changed unfavourably. It must be concluded that the decrease of the relative solubility of soil phosphorus is at least partly due to considerable migration of phosphorus from the arable layer to the subsoil. Obviously the most soluble fractions of soil phosphorus will be especially affected in this way.

On this soil a difference of 13 units corresponds to about 190 kg P_2O_5 per hectare. This considerable leaching of phosphorus is remarkable. De Vries and van der Paauw [24] have demonstrated important vertical migrations of phosphorus under the influence of leaching in similar humic sandy soils with a high content of water soluble phosphorus.

c. *Effect of alternating periods with different rainfall on the content of exchangeable potassium*

A clear relation between the trend of the content of exchangeable potassium * and that of rainfall has been found at the experimental

* Determined by extraction with 0.1 *N* hydrochloric acid.

field PO 7 layed down to grass on a humic sandy soil for the period 1930 to 1938 (Fig. 6). The content of exchangeable potassium has increased in dry and decreased in wet periods. The differences

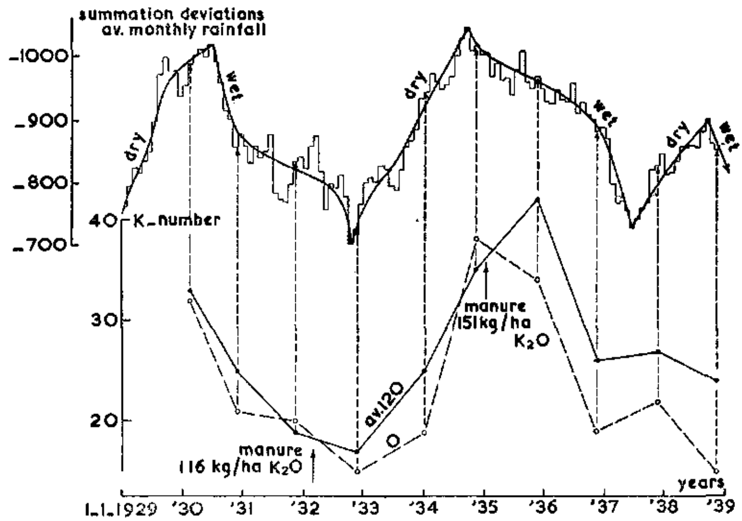

Fig. 6. Time course of contents of exchangeable potassium without and with potash dressing (average 120 kg/ha) on grassland at experimental field PO 7 compared with summation curve of deviations from average monthly rainfall (from Fig. 1).

cumulatively effected by prolonged rainfall periods appreciably surpass those resulting from widely differing potassium dressings (0, 40, 80, 120, 160 and 240 kg K_2O per ha; Fig. 6 only shows 0 and the average of 80, 120 and 160). In fact the non-fertilized plot was supplied with potassium at a rather moderate level after the first cut as the excrements of cattle which were allowed to graze on the whole field including plots dressed with potassium; in addition stable manure at the rate of 116 and 151 kg K_2O per ha was applied in 1932 and 1935 respectively. The rise in the content of exchangeable potassium observed on the non-fertilized plot was probably due to a preponderantly upward displacement of water and could not possibly have occurred to such an extent if no potassium had been supplied at all.

d. *Effect of alternating periods of different rainfall on the soil fertility complex*

Since no other soil factors were determined annually on the long term experimental fields nothing can be said with certainty about their behaviour. It seems reasonable, however, to assume that the effect of alternating periods of different rainfall on soil fertility can not be restricted to the three factors considered. This conclusion is supported by the fact, which will be discussed below, that the availability of soil nitrogen also displays gradual fluctuations corresponding to those of rainfall periods. It is likely, therefore, that physical, biological and other chemical soil factors may also be affected in a similar way. It must be assumed, therefore, that the total soil-fertility complex is affected and that it fluctuates under the cumulative influences of alternating rainfall periods.

A co-operative study of the partial effects of these periods on the soil has been started at the Institute for Soil Fertility at Groningen.

4. ALTERNATING PERIODS OF DIFFERENT RAINFALL, PERIODIC FLUCTUATIONS OF SOIL FERTILITY AND YIELDS

Kamerling [11], Beveridge [3], Bean [1] and van der Paauw [14 15], have suggested that periodic fluctuations of crop yields are due to meteorological periodicities, but thus far no definite proof has been given. An approximately similar pattern of fluctuation of yield has been observed with wheat, barley, rye, oats, peas, beans, potatoes, canary-grass, spinach, caraway, and sugar beet (seed) on different soils in the Netherlands. Some examples are given for yields of wheat and peas grown on clay soils in the province of Groningen and of rye grown on the humic sandy soils in the province of Drente to the south of Groningen (Fig. 7). The yield figures were derived from the official statistics based on the averages of numerous estimations of yield.

There is a noticeable agreement between the sequence of the yield of crops notwithstanding the ecological differences between plants and soils.

Since 1950 the yields of peas have been lower than before and this might be ascribed to a considerable increase of rainfall. This is not the case, however for wheat. It may be that the growing of higher productive strains has exceeded the harmful effect of excessive rainfall. Yields obtained after too great a time interval may be less comparable.

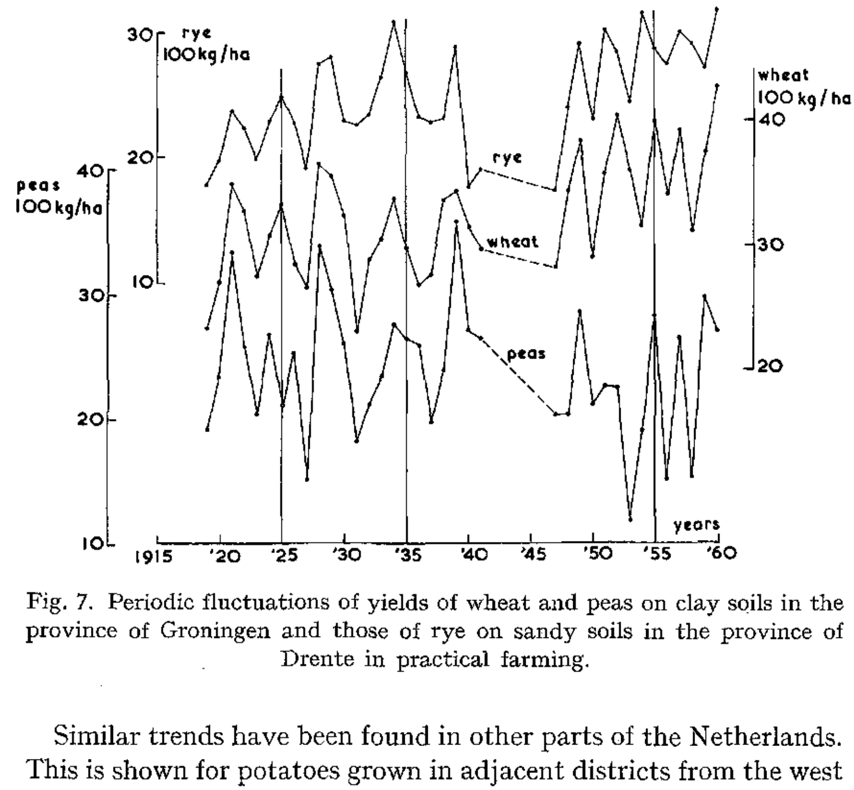

Fig. 7. Periodic fluctuations of yields of wheat and peas on clay soils in the province of Groningen and those of rye on sandy soils in the province of Drente in practical farming.

Similar trends have been found in other parts of the Netherlands. This is shown for potatoes grown in adjacent districts from the west (Zeeland) to the east (Gelderland) (Fig. 8). For a comparison the sequence of yields of a region in Groningen (northeastern part of the country) has also been represented.

Periodic trends in yield have also been observed on single experimental plots although here different crops have been grown in succession. To demonstrate this the yields in single years have been expressed as a percentage of the average yield of the same crop calculated over all the years. These relative yields have been plotted against time. Results from the experimental field Pr 42 show a similar pattern of yield fluctuations as has been noted in practical farming (compare the curve in Fig. 9 with the curve of rye in Fig. 7 obtained on the same soil type). Again, in the years 1941 to 1946 for

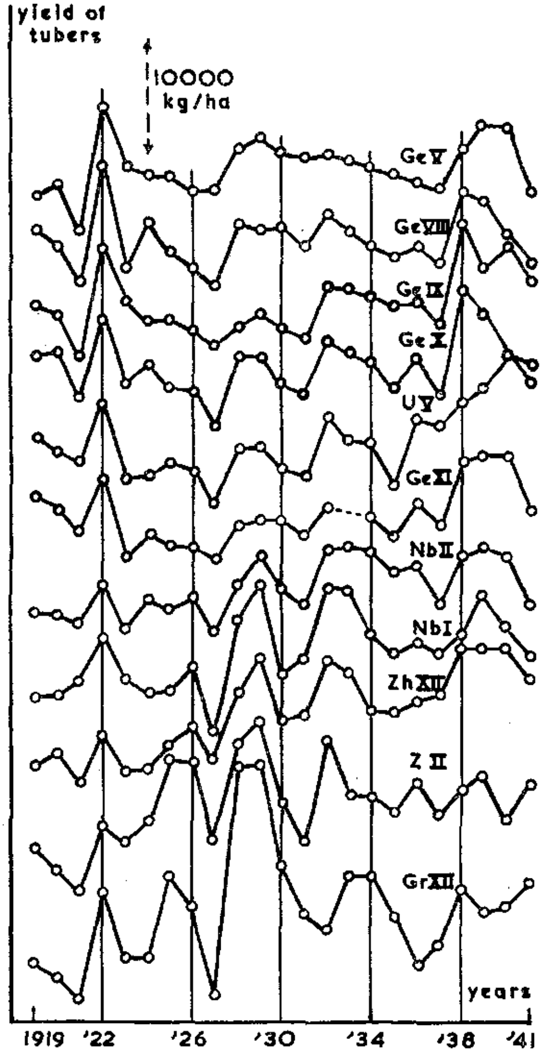

Fig. 8. Trends of yields of potatoes in practical farming going from west (below) to east (above) in the Netherlands. Lowest curve relates to Groningen in the northeastern part.

* Gr XII, Groningen, Westerwolde; Z II, Zeeland, island of Schouwen en Duiveland; Zh XII, Zuidholland, island of Voorne en Putten and Rozenburg; Nb I, Noordbrabant, northwestern clay district; Nb II, Noordbrabant, Land van Heusden en Altena; Ge XI, Gelderland, Bommelerwaard; U 5, Utrecht, Kromme Rijn; Ge X, Gelderland, Tielerwaard; Ge IX, Gelderland, Betuwe; Ge VIII, Gelderland, De Lijmers; Ge V, Gelderland Graafschap Zutfen.

which the official figures are untrustworthy a regular wave is found on the experimental field.

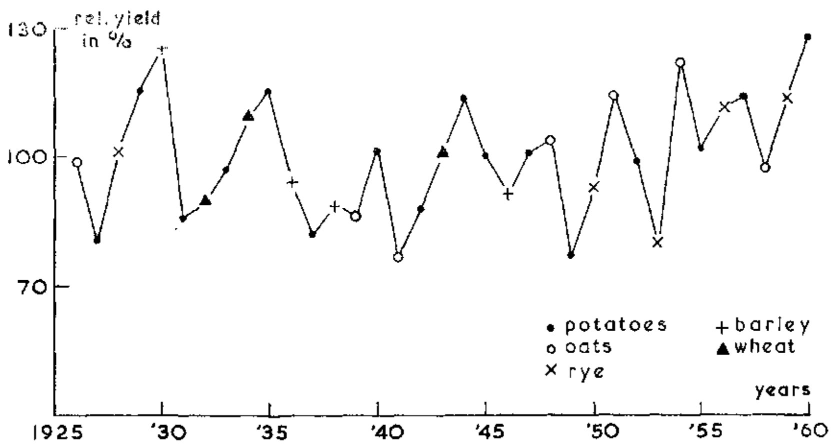

Fig. 9. Periodic fluctuations of relative yields of different crops grown in rotation at the experimental field Pr 42.

It is assumed that the periodic changes in soil fertility factors have been effected by the alternation of periods of different rainfall. From the similarity of the changes and those of yields of different crops (note the gradual development of increases and decreases (Fig. 10) the conclusion is drawn that the periodicity of crop yields may be attributed to these fluctuations of soil fertility.

In Fig. 10 the summation curve of the deviations from the average precipitation for the period of 1915–1959 (being part of the curve constructed for the years 1880 to 1959, see Fig. 1) has been compared with the average trend of soil pH on sandy soils (from Fig. 4) and that of wheat on marine clay soils (from Fig. 7). The averaged trend in the yield of potatoes and cereals (rye or oats), grown simultaneously and in succession on the two halves of a long-term experimental field (registered as Pr 8 and Pr 9 started in 1881 on a soil rich in humus) has also been added. It is shown for the period 1914 to 1934 only.

Increases of wheat yields more or less closely correspond to decreases of pH occurring in dry periods and conversely. Corresponding trends in rainfall and in the average of the percentage yields of cereals (rye or oats) and of potatoes (yields expressed as a percentage of the average yields obtained with each crop separately over all years) at the experimental field Pr 8+9 are also apparent. The

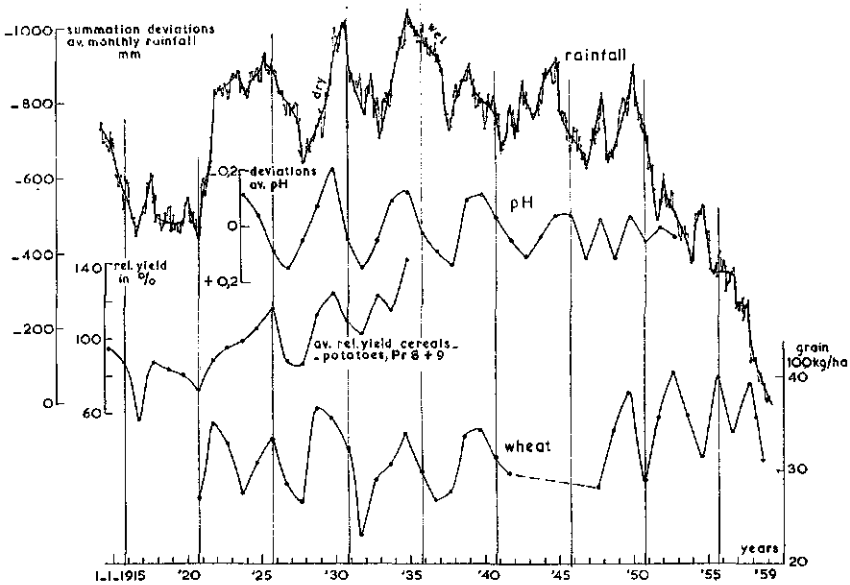

Fig. 10. Periodic fluctuations of soil pH (from Fig. 4), yields of wheat in practical farming (from Fig. 7) and average relative yields of potatoes and cereals (rye or oats) at the experimental field Pr 8+9 compared with summation curve of deviations of the average monthly rainfall (from Fig. 1).

rather close agreement between the average yields found on this very humic sandy soil and the yields of wheat grown in practical farming on marine clay soils is remarkable.

Kamerling[11] in 1916 has already pointed to the occurrence of cyclic fluctuations of the yields of the Broadbalk field at Rothamsted Experimental Station in England, where wheat is grown continuously. The average yields in the first half century of those plots dressed with manure or artificial fertilizers and that left unfertilized are compared with the summation curve of the deviations of average rainfall (calculated for each month separately) in south-eastern England * for the period 1843–1893 (Fig. 11).

* Meteorological stations: 1843–1863 London (Greenwich), 1864–1865 London (Cambden Tower), 1866 Ware, 1867–1870 Northhampton (Wellingborough), 1871–1874 Bayfordbury, 1874–1880 St. Albans (Bayfordbury), 1881–1893 Hertford (Bayfordbury).

Alternating rainfall periods occurred, especially from 1854 to 1879. The lowest yields are found at the end of wet periods but

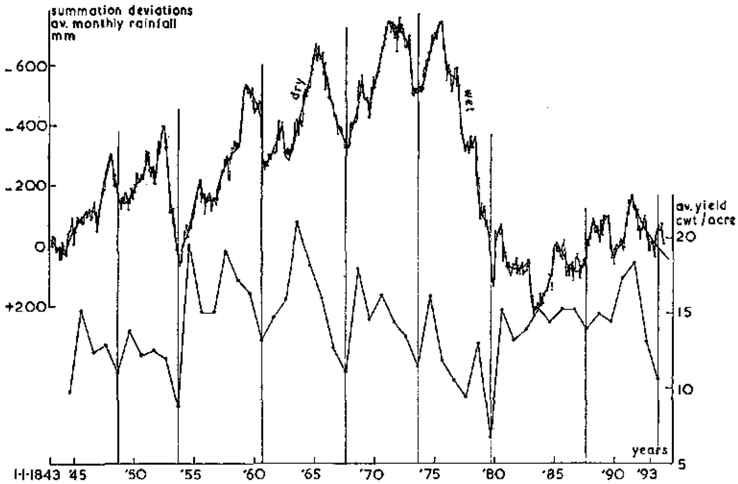

Fig. 11. Periodic fluctuations of wheat yields from 1844 to 1893 at Broadbalk Field of Rothamsted Experimental Station compared with summation curve of deviations of average monthly rainfall (1843–1893) in Southeast England (calc. for each month separately).

different from the results in the Netherlands (Fig. 7, 9) the highest yields occurred in the first year of a dry period. This difference might be connected with the continuous cultivation of the same crop. As soon as alternating periods of rather long duration were succeeded by shorter periods (from 1880), the periodic fluctuations almost ceased. The undulation reappears in 1890 clearly corresponding to the pattern of rainfall.

As it is unreasonable to claim a direct causal effect of preceding alternating rainfall periods on the crops, it must be concluded that the periodic course of yields is due to changes in the soil. They indicate a "memory" of weather conditions prevailing in a previous period. The fertility status of the soil should be regarded as an intermediary between the fluctuations of weather and crop yields. Evidently the fluctuations in soil fertility induced by cumulative effects of periods of different precipitation are of paramount importance for the control of crop yields.

5. ALTERNATING PERIODS OF DIFFERENT RAINFALL EFFECTING PERIODICAL YIELD RESPONSES TO FERTILIZING

The contents of water-soluble phosphorus and of exchangeable potassium and pH which are affected by prolonged rainfall periods are major factors controlling yield. Numerous field and pot experiments [16 17 21] have given clear evidence of this.

A continuous change of these factors may considerably affect the responses to P- and K-fertilizers and liming.

Nitrogen is a most important growth factor. It is known that the content of soluble nitrogen in the soil greatly depends on meteorological conditions (Harmsen [9], van der Paauw [20]). The author and others [4 8 13 20] have shown that the response to nitrogen dressing is largely controlled by relatively small differences in the total amount of winter rainfall. It might, however, be possible that the nitrogen status is also affected in the long run by cumulative effects of alternating rainfall periods. Experimental data about the changes in the nitrogen status of the soil and sub-soil are insufficiently available for this purpose, but evidence may be obtained from yields of plots not dressed with nitrogen.

Evidence is given below of periodical responses in yield to dressings of fertilizers and to liming. These bear a relation to alternating rainfall periods. No definite data are available concerning the response to potassium. The response to potassium dressing at the experimental field PO 7 mentioned above was too small and the duration of the experiment too short to provide a definite answer to this question and the same is true of other cases.

a. *Periodic response to lime as related to the fluctuations of pH-H_2O*

Periodic fluctuations of pH have been observed on the experimental field Pr 10 on humic sandy soil (Fig. 12, compare with Fig. 4). The responses of potatoes, wheat, rye, and oats to pH proved to be different. The need to compare their different reactions made it necessary to convert the yields of the first three crops at low pH without NPK dressing (as a percentage of those at high pH with ample NPK) to relative yields of oats on the basis of the respective correlations with pH found for each crop separately. Results obtained with crops grown less consistently have been omitted.

Periodic fluctuations of these relative "oats" yields are found to correspond clearly to periodic fluctuations of pH (Fig. 12). Thus, rises of pH occurring in wet periods which normally lead to a gradual decrease of yield are correlated with rising yields at low pH level. Yields obtained at high pH and ample dressing, expressed as per-

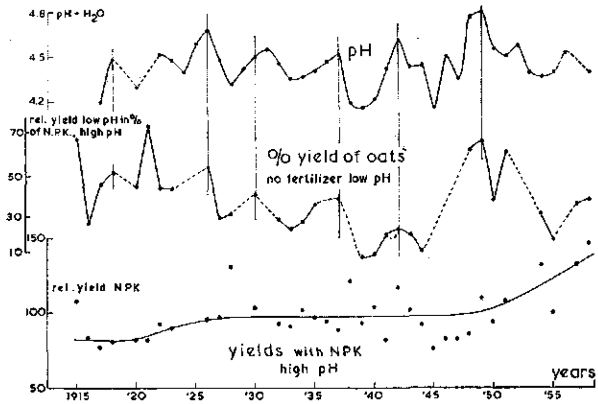

Fig. 12. Periodic fluctuations of relative yields (in percentage of yield with full dressing and high pH) of different crops at low pH without fertilization converted into relative yields of oats compared with periodic trend of pH at the experimental field Pr 10.

centages of the average yields of the relevant crops show these periodic fluctuations weakly or not at all (lowest curve). Hence it follows that the response of crop yields to lime (response to different pH value) is also periodic.

The pH is generally considered as indicator of the state of base saturation of the soil. The agreement found between the trends of pH and the lime responses might suggest a direct causal relation. This might be doubted, however. As a matter of fact fluctuations of pH determined in water suspension are considerably affected by differences in salt content (Bruin [5]). These fluctuations of salt content are brought about by vertical up and down migrations of soil water. Salt content increases in dry periods causing a decrease of pH. Considerably smaller fluctuations are observed when the pH is determined in KCl solution.

b. *Periodic phosphorus response corresponding to the trend of the content of water-soluble phosphorus*

Clearly undulating responses to phosphorus dressing – obviously related to corresponding changes of the content of water-soluble phosphorus – are demonstrable on the oldest experiment field in the Netherlands (Fig. 13). This started in 1881 on a peaty soil (reclaimed moor soil). Both halves have borne in alternate years potatoes. Relative yields of this crop grown on the plot without phosphorus dressing from the beginning are expressed as a percentage of yields obtained with complete NPK dressing. No data are available for the years 1909, 1911, 1913 and 1915. From 1900 the yields are compared with the summation curve of the deviations from average monthly rainfall (calculated for each month separately). It is reasonable to assume that the response to phosphorus is determined by the status of the soil at the beginning of the growing season. Therefore, yields have not been plotted in the figure at harvest time but earlier (1st of April).

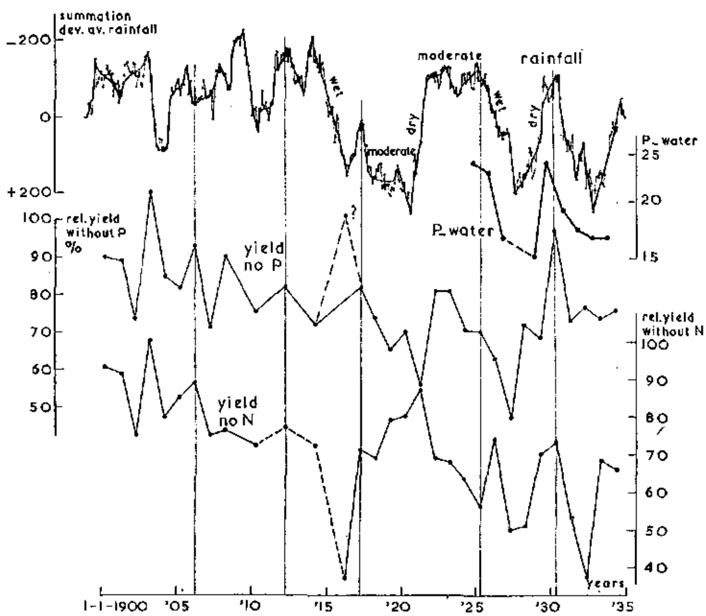

Fig. 13. Periodic fluctuations of relative yields of potatoes obtained without phosphorus dressing in per cents of those with complete dressing at the experimental field Pr 8+9 compared with periodic fluctuations of content of water-soluble soil phosphorus and with summation curve of deviations of average monthly rainfall (from Fig. 1). Below: trend of relative yields without nitrogen dressing at same field.

Data concerning the content of water-soluble phosphorus determined at each harvest are available since 1924 (Not determined in 1927). According to the results of numerous field experiments with potatoes the content of water-soluble phosphorus gives a very reliable indication of the availability of soil phosphorus to potatoes. The data in Fig. 13 refer to the plot with complete NPK dressing. Those obtained on the plot without phosphorus dressing are much lower (3–5) and so are determined less accurately. However, fluctuations of phosphorus contents are similar in the two cases.

Fluctuations of the content of water-soluble phosphorus parallel the alternating periods of rainfall. The content decreases in wet periods and rises in dry ones (same as Fig. 5).

The relative yields obtained without phosphorus dressing show an undulation closely parallel to the fluctuations of the phosphorus content. This leads to the conclusion that fluctuations of phosphorus response are probably due to fluctuations of available phosphorus in the soil. The fluctuations of yields obtained when complete NPK dressing was applied appeared to be less pronounced and less regular.

Though most results confirm the conclusion that the response to phosphorus was dependent upon rainfall in the preceding period some deviations occurred in 1921 and 1916. The low yield of 1921 is rather unexpected. This might be due to the extremely dry conditions. The high relative yield in 1916 indicated by query-mark and dotted lines) is altogether abnormal for it followed a long period of high rainfall. In this case the yield was about the same as that of the NPK plot. However, the latter was the lowest yield of this plot in all years of the experiment. The reason for this may be very low availability of soil nitrogen as demonstrated by an extremely low yield without nitrogen dressing (Fig. 13, curve below). It seems acceptable that the rather low nitrogen dressing (according to modern view) of the NPK plot was insufficient for the needs of the crop. It may therefore be that deficiency of nitrogen weakened the response to phosphorus.

c. *Periodic nitrogen response*

Nitrogen response of crops greatly depends on the amount of rainfall during the preceding winter months (Russell [22], Fisher [8], Boyd, Garner and Haines [4], Lehr and Veen [13], van der Paauw [20]). This statement does not exclude the fact that it is also affected by alternating long rainfall periods. The effect of the latter, however, may easily be overshadowed by the dominant effect of rainfall in the preceding winter.

Fluctuating nitrogen responses probably due to the alternation of periods of different rainfall, can be demonstrated on two experimental fields. It is not impossible that the effect of winter rainfall was less dominant in both cases. The first one relates to the experimental field Pr 935 on a newly reclaimed peat soil (peat covered with a sand layer) where the amount of nitrogen – present in the superficial layers of the soil which are accessible to leaching – is low at the beginning of winter rains. The other case relates to the plot which received no nitrogen dressing after 1881 in the long term experiment Pr 8+9. Probably the conditions are similar here. In this regard it may be remembered that Fisher [8] was not able to find any effects of winter rainfall on the no-nitrogen plot of the Broadbalk field of Rothamsted Experimental Station.

1. The experimental field Pr 935. The amounts of nitrogen applied vary from zero to very high values. The design of the experiment is different each year. As a consequence plots not supplied with nitrogen in one year have been dressed in the previous year. Potatoes and rye have been grown simultaneously in most years.

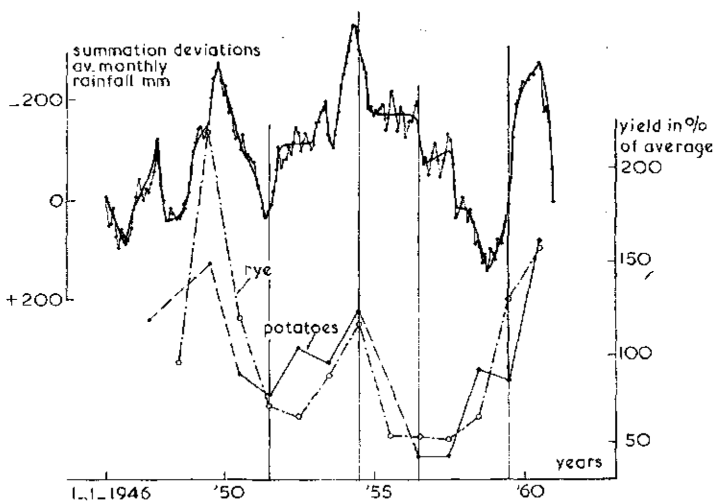

Fig. 14. Periodic fluctuations of yields of potatoes and rye grown simultaneously without nitrogen dressing (in per cent of average yields without N-dressing of whole period) at the experimental field Pr 935 compared with summation curve of deviations of average monthly rainfall in period 1946–1961 at Ter Apel (calc. for each month separately).

Yield fluctuations are clearly periodic where no nitrogen was applied (Fig. 14) but are less variable with nitrogen. It follows that the differences between the plots with and without nitrogen (responses to nitrogen) are also periodic (Fig. 15).

In Fig. 14 the total yields of dry matter obtained without nitrogen have been expressed as percentages of the average of the yields without nitrogen in all years. In general the agreement between the course of yields of both crops is striking (correlation

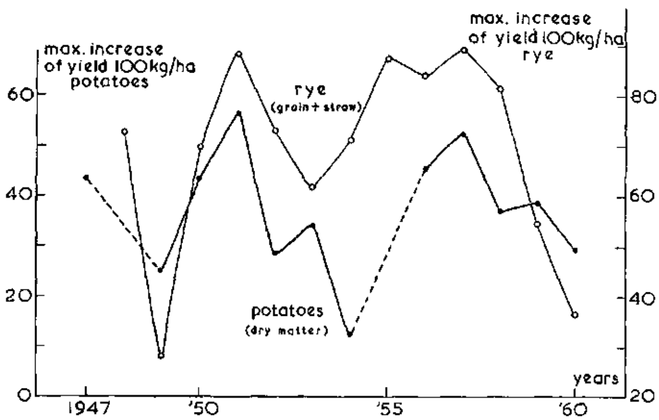

Fig. 15. Periodic yield responses to optimum nitrogen dressing of potatoes (dry matter) and rye (grain + straw) expressed as increases of yields in kg per ha at the experimental field Pr 935.

coefficient for these yields $r = 0.81$). However, the main growth periods of rye and potato are not simultaneous and their ecological characteristics are not comparable. It is likely, therefore, that the agreement found must be ascribed to identical soil conditions. In all probability the availability of nitrogen controlled the growth in both cases.

The amounts of nitrogen available in each year may be controlled by the alternation of periods of different rainfall. The course of the yields without nitrogen in the period 1946 to 1960 (Fig. 14) reflects the alternating periods of different rainfall. It is true that there are also indications of a special effect of rain during the preceding winter. The high yields of 1949 and 1954 especially may be attributed to a dry winter. However, the regularly rising and falling course of the curves seems to point to a specific effect of rainfall over relatively long periods.

2. Long term experimental field Pr 8+9. Dressing with nitrogen fertilizers started on the NPK-plot in 1881. The size of the dressing, 60 kg of N per ha supplied to potatoes, was increased to 75 kg in 1912 (63 in 1918) and to 90 kg in 1924. The gradual decrease of relative yields without nitrogen (as a percentage of yields of the completely dressed plot) is probably due both to depletion of the unfertilized plot and to the increased dressing of the fertilized one as well.

Relative yields obtained without nitrogen since 1900 represented in relation to the summation curve of the deviations from average rainfall (calculated for each month separately) can also be compared with relative yields obtained without phosphorus dressing (Fig. 13). Between 1926 and 1934 especially, but also less clearly between 1900 and 1918, the variations in yields correspond to those of precipitation and of relative yields of the plots without phosphorus. The extremely low yields without nitrogen in 1916 (mentioned already) 1927 and 1932 may be explained by preceding wet periods.

The agreement with the variations in rainfall fails from 1921 to 1926. In the period of rather constant rainfall from the end of 1918 till the autumn of 1920 the relative yields without nitrogen increase gradually. The maximum in 1921 can be accounted for by the abrupt change of the weather which had been extremely dry from the middle of 1920 till the end of 1921. Then in a new period of moderate rainfall which was only slightly drier than that of 1918–1920 yields continually fell. It is of course strange that in this second period, yields behaved in an opposite manner to those in the first one. This might indicate that the soil is differently affected, with respect to nitrogen, when a period of moderate rainfall follows a very wet one from when a period of moderate rainfall follows a very dry one.

From the differences between the reponses to nitrogen and to phosphorus, it might be concluded that the mechanisms controlling the availability of these elements are not essentially the same.

Changes in the amounts of available nitrogen may contribute largely to the causation of periodic fluctuations of yields. In western Europe nitrogen is the paramount growth controlling factor.

d. *Potassium response*

No similar reliable experimental data for potassium are available. Nevertheless on the basis of the results of numerous field experiments it is likely that differences in potassium such as have been observed on the experimental field PO 7 (p. 162), are important for grass growth and fodder quality. It is clear, therefore, that periods of high rainfall may gradually promote potassium deficiency in the crop, and periods of low rainfall an excessive absorption of potassium by the grass. In this respect it is important to note that differences in potassium status induced by rainfall appear to be much greater than those brought about by very different practices of fertilizing (Fig. 6).

DISCUSSION

It is evident that important differences in the fertility of the soil originate from alternations of rainfall. It may be assumed that many soil factors are affected similarly. Fluctuations of nitrogen availability such as have been observed might also be affected by fluctuations in the physical conditions. Microbiological behaviour of the soil may also depend on physical and chemical changes and in its turn affect fertility status and crop growth.

The economic importance of the alternation of periods of different precipitation appears from a comparison of crop yields. After a series dry years yields of wheat and rye in practical farming were sometimes $1\frac{1}{2}$ times as high as those after a succession of wet years. With a more sensitive crop such as peas a ratio of about 3 was found. These figures are averages for whole provinces and they hide the actual differences between smaller areas, for on soils of low productivity especially, the fluctuations may be considerably greater.

Thus far agronomic meteorology has limited its activities mainly to the study of correlations between crop yields and factors directly affecting plant growth. Little attention has been paid to the dominant role of soil fertility in the relations between weather and crop yields. Yet it is probable that the weather in a preceding period because it determines the fertility status of the soil, is very important for agricultural production.

If it is agreed that the yield largely depends on the fertility status of the soil and that changes in fertility status are slow it may be possible to predict future yields.

Attempts have been made to determine the deviations of pH from the average trend of pH and to correlate these deviations with the corresponding deviations in yield of crops in practical farming from the average trend in the period 1924 to 1939. For this purpose the averages of the deviations of pH determined at harvesting and in the preceding year have been used. It is assumed that these averages give the best approximation to the actual average pH at the beginning of the growing season. Correlations have been determined for different crops separately and also for the averaged deviations from the normal yields of wheat, peas and rye. In the latter case the correlation coefficient amounted to $r = -0.79$.

The high correlation found indicates the possibility of reasonably reliable predictions of yields. A necessary premise is, however, that wet and dry periods are rather regularly alternating.

The conclusion that the soil fertility is largely controlled by cumulative effects of weather and that the fluctuations affected by weather preponderantly influence crop yields, is of great practical importance. Attempts may be made to adjust fertilization in the field so as to attain a better control of phosphorus, potassium and nitrogen supply and of possible other factors. This may contribute to the attainment of more stable agricultural production at a level as high as possible.

Future research will be directed to the disentangling of the major soil factors responsible for the fluctuations of crop yields under the cumulative effect of weather.

SUMMARY

The phenomenon of cyclic fluctuation of factors is common in meteorological literature.

More or less cyclic alternations of periods of different rainfall appear to be especially evident from 1910 to the present day and also from 1854 to 1879 (Figs. 1, 11, 14).

The soil fertility status is related to the prevailing weather conditions. Changes in the amount of precipitation give rise to considerable changes in the fertility of the soil.

Periodic fluctuations of soil factors such as the contents of water-soluble phosphorus (Figs. 5, 13) of exchangeable potassium (Fig. 6) and the pH (Figs. 4, 12) originate from gradual and cumulative effects of rainfall in alternating periods of markedly different precipitation. The contents of phos-

phorus and potassium rise in dry and fall in wet periods, the pH (of soil in water suspension) reacts in the opposite sense (Fig. 3, 10).

Periodic responses of crop yields to the application of phosphorus dressings opposite in sense to the periodic fluctuations of the content of water-soluble phosphorus (being large if content is low) have been observed (Fig. 13). Since the content of water soluble phosphorus has been proved to determine the response of potatoes to phosphorus dressing it is likely that the relation between the two periodic phenomena is causal.

Periodic fluctuations of pH also correspond to those of crop yields over a range of low pH (Fig. 12). It is doubtful whether this is also to be considered as a direct causal relation.

Similarly periodic responses to nitrogen dressing are found on soils with a poor production of available nitrogen (Figs. 13, 14, 15). Obviously the amount of available nitrogen is affected by alternating rainfall periods though the effect of winter rainfall on nitrogen response is paramount in most cases [20].

The differences noted in the content of exchangeable potassium in grassland are considerable and surpass those effected by different fertilizer practices. It is assumed, therefore, that the effect of these fluctuations on the crop may be important, but no reliable data are available as yet.

Distinct periodic fluctuations of crop yield which have been observed frequently with many crops on a variety of soils in practical farming and on experimental fields (Figs. 7, 9), must be attributed to periodic fluctuations of soil fertility. In their turn the latter are controlled by the alternation of periods of different rainfall (Fig. 10). The pattern of these alternations is rather similar in adjacent districts and only slowly changes from north to south and from east to west in the Netherlands (Fig. 8).

A similar pattern of rainfall to that observed in the Netherlands was apparent between 1844 and 1893 in England. The course of yields of wheat grown continuously on the Broadbalk field of Rothamsted Experimental Station closely corresponds to this distribution of rainfall (Fig. 11).

The response of yield to the alternating rainfall periods is economically important. The average yields of wheat and rye in Dutch provinces after some dry years amount to 1½ times of those obtained after a succession of wet years. Similarly the yield of a more sensitive crop like peas is about 3 times higher. Over smaller areas especially on infertile soil these differences may be still larger.

It appears theoretically possible to eliminate yield fluctuations at a high level of production by means of appropriate measures of fertilization and soil management.

Since the fluctuations of crops yields may be ascribed to changes of the actual soil fertility status, it seems possible to forecast yields on the basis of the determination of the deviations of soil factors from the normal trend.

RÉSUMÉ

Variations périodiques des récoltes et des effets de la fumure sous l'influence de périodes alternantes de hautes et basses précipitations

La litérature météorologique fournit de nombreux exemples de variations cycliques de facteurs climatologiques. Spécialement dans les périodes de 1910 à aujourd'hui et de 1854 à 1879 on peut reconnaître des périodes de 2 à 3 années avec hautes et basses précipitations (fig. 1, 11, 14).

Les conditions climatologiques déterminent l'état dans lequel se trouve le sol. Un changement dans la quantité de précipitations exerce des changements considérables dans la fertilité des sols.

Des variations périodiques de certains facteurs du sol comme par exemple le pH (fig. 4, 12) ou la teneur en acide phosphorique soluble à l'eau (fig. 5, 13) ou en potasse échangeable (fig. 6) ont été constatées. Celles-ci correspondent avec les écarts périodiques des précipitations moyennes (déterminées pour chaque mois) et sont attribuées aux effets cumulatifs des précipitations Les teneurs en acide phosphorique et en potasse augmentent dans les périodes sèches et diminuent pendant les périodes humides. Le pH (déterminé dans une solution acqueuse) montre une relation contraire (fig. 3).

Au cours des années on observe une périodicité dans l'effet de la fumure phosphatée sur les récoltes contraire à la teneur du sol en acide phosphorique soluble à l'eau (fig. 13). Parce que dans beaucoup de nos expériences cette teneur en acide phosphorique s'est rélevée un norme précis pour l'assimilation de l'acide phosphorique par les cultures, il doit exister probablement une relation causale entre cette teneur en acide phosphorique du sol et l'effet de la fumure.

A un niveau bas du pH les récoltes correspondent positivement aux changements du pH (fig. 12). Ceci est remarquable, parce qu' une élévation des valeurs pH est justement provoquée par une augmentation des précipitations, défavorable aux récoltes, de sorte qu'elle donnait souvent une corrélation négative. Il est cependant douteux s'il existe dans le premier cas véritablement une relation causale entre le pH et la récolte.

Des variations périodiques de l'effet d'une fumure azotée furent constatées dans les sols dont la teneur en azote mobilisable était basse (fig. 13, 14, 15). Il semble que cette teneur est également influencée par la quantité de précipitations dans les périodes successives. Dans le pluspart des cas les précipitations de l'hiver précédant exercent probablement la plus grande influence [20].

Les différences en teneur de potasse échangeable dans les prairies permanentes sont plus fortes que les différences que les fumures ont pu provoquer dans le sol. Nous supposons donc que ces fluctuations sont très importantes pour la plante, quoi qu'il nous ait pas encore été possible d'en fournir la preuve au moyen d'expériences.

Les variations périodiques remarquables des récoltes de cultures diverses sur différents sols constatées de façon générale aussi bien dans la pratique que sur les champs d'essais (fig. 7, 9) sont attribuées à ces changements

périodiques de la fertilité du sol. Ces derniers se forment sous l'influence des variations de précipitations (fig. 10). Cette périodicité suit un cours correspondant dans les régions avoisinantes (fig. 8).

En Angleterre les variations périodiques des récoltes sur le Broadbalk field avec monoculture de froment à la station de recherches agronomiques de Rothamsted entre 1844 et 1893 correspondent de même manière avec la hauteur des précipitations dans les périodes successives, exactement comme il en est le cas pour les années postérieures dans les Pays Bas (fig. 11).

Il est d'une importance économique capitale que les récoltes sont tellement fortement liées aux périodes continues de précipitations constantes. Les récoltes moyennes de froment et de seigle aux Pays Bas sont après quelques années sèches à peu près $1\frac{1}{2}$ fois aussi élevées qu'après quelques années humides. Les pois, une culture plus sensible, donne même une récolte moyenne 3 fois si haute. Ces écarts de rendements sont souvent encore plus forts sur des petites surfaces et sur les sols moins fertiles.

En principe il est possible de réduire considérablement ces variations des récoltes par des fumures et traitements du sol adéquates.

Si l'on réussirait à déterminer d'anvance les écarts de la fertilité du sol, il sera même possible de prédire la richesse des récoltes à venir.

ZUSAMMENFASSUNG

Periodische Schwankungen der Erträge und der Düngerwirkungen unter dem Einfluss abwechselnder Perioden mit hohen oder niedrigen Niederschlagsmengen

In der meteorologischen Literatur sind viele Beispiele zyklischer Schwankungen von Witterungsfaktoren beschrieben worden.

Besonders während der Jahre 1910 bis heute und auch von 1854 bis 1879 können, oft 2–3 Jahre dauernde, Perioden von hohen bzw. geringen Niederschlagsmengen erkannt werden (Abb. 1, 11, 14).

Die herrschenden Witterungsverhältnisse sind bestimmend für den Zustand worin der Boden sich befindet. Eine Änderung der Niederschläge veranlasst erhebliche Änderungen der Bodenfruchtbarkeit.

Periodische Schwankungen verschiedener Bodenfaktoren, so wie der pH-Werte (Abb. 4, 12) oder des Gehaltes wasserlöslichen Phosphors (Abb. 5, 13) oder austauschbaren Kalis (Abb. 6) wurden festgestellt. Diese korrespondieren mit den periodischen Abweichungen von den durchschnittlichen Niederschlagsmengen (für jeden Monat bestimmt) und werden zurückgeführt auf die kumulativen Wirkungen der Niederschläge. Die Phosphor- und Kaligehalte steigen in trockenen und nehmen ab in nassen Perioden; der pH-Wert (in wässeriger Suspension) zeigt das entgegengesetzte Verhältnis (Abb. 3).

Eine im Laufe der Jahre dem Gehalt wasserlöslichen Bodenphosphors entgegengesetzt schwankende Düngerwirkung des Phosphors auf die Erträge konnte festgestellt werden (Abb. 13). Weil der Gehalt wasserlöslichen Bodenphosphors sich bei vielen unserer Untersuchungen für die Phosphor-

entnahme als massgebend erwiesen hat, ist eine kausale Beziehung zwischen Phosphorgehalt des Bodens und Düngerwirkung wahrscheinlich.

Bei niedrigem pH-Niveau korrespondierten die erhaltenen Erträge positiv mit den Schwankungen des pH-Wertes (Abb. 12). Das ist bemerkenswert, da Steigerungen der pH-Werte gerade durch, für die Erträge ungünstige, nasse Witterung hervorgerufen werden, wodurch sonst oft eine negative Korrelation festgestellt wurde. Ob in dem ersten Fall wirklich eine direkte positive kausale Beziehung zwischen pH-Wert und Ertrag besteht, ist jedoch zweifelhaft.

Periodische Schwankungen der Wirkung von Stickstoffdüngern wurden festgestellt auf Böden mit geringen Mengen an mobilisierbarem Stickstoff (Abb. 13, 14, 15). Offenbar wird auch der Gehalt an leicht verfügbarem Stickstoff durch die Niederschlagsmengen der aufeinander folgenden Perioden beeinflusst. In den meisten Fällen haben wahrscheinlich die Niederschläge des letzten Winters den grössten Einfluss [20].

Die gefundenen Unterschiede im Gehalt austauschbaren Kalis auf Dauergrassland übersteigen die Unterschiede welche unter Einfluss weit auseinanderlaufender Düngergaben im Boden entstehen. Angenommen wird daher, dass diese Schwankungen für die Pflanzen sehr wichtig sind, obwohl es noch nicht gelungen ist dies anhand der Versuchsergebnisse zu beweisen.

Auffallende periodische Schwankungen der Erträge verschiedener Pflanzenarten auf verschiedenen Böden welche in der landwirtschaftlichen Praxis und auf verschiedenen Versuchsfeldern ganz allgemein festgestellt wurden (Abb. 7, 9), werden auf diese periodisch auftretenden Änderungen der Bodenfruchtbarkeit zurückgeführt. Letztere entstehen unter dem Einfluss von den Schwankungen des Niederschlags (Abb. 10). Ein übereinstimmender Verlauf dieser Schwankungen wurde in angrenzenden Gebieten beobachtet (Abb. 8).

In England korrespondierten die wellenartigen Schwankungen der Erträge bei ewigem Weizenbau auf dem Broadbalk Felde der Rothamstedschen Versuchsstation 1844–1893 in ähnlicher Weise mit der Menge der Niederschläge in den aufeinander folgenden Perioden wie es in späteren Jahren auch in den Niederlanden festgestellt wurde (Abb. 11).

Oekonomisch ist es von grosser Bedeutung, dass die Erträge auf lange anhaltende Perioden konstanter Niederschlagsmenge stark reagieren. Die mitleren Weizen- und Roggenerträge in den Niederlanden sind nach einigen trockenen Jahren im Durchschnitt etwa 1½ Mal so hoch als nach einigen nassen Jahren. Bei einer empfindlicheren Pflanze, wie die Erbse, ist der Ertrag dann wohl 3 Mal so hoch. Die Unterschiede sind auf kleinerer Bodenfläche und auf unfruchtbaren Böden oft noch grösser.

Es ist prinzipiell möglich die Ertragsschwankungen durch zweckmässige Eingriffe bei der Düngung und Bodenbehandlung erheblich zu mässigen.

Es wurde auch gewiesen auf die Möglichkeit die zu erwartenden Erträge vorauszusagen, wenn es gelingen würde die Abweichungen der Bodenfruchtbarkeit zuvor festzustellen.

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