ROTHAMSTED RESEARCH

Report for 1939-45

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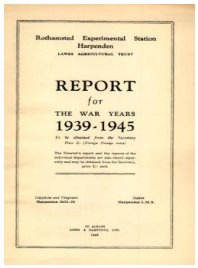

Statistics Department

F. Yates

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DEPARTMENT OF STATISTICS

By F. YATES

The Statistical Department was originally founded in order to carry out analyses of the accumulated results of the classical experiments at Rothamsted, and to provide statistical assistance for other departments of the Station, but it soon became apparent that considerable researches into statistical theory and method were also required. The results of these researches into theory and method are naturally of interest to research workers in many fields, and the Department has been continuously consulted by outside bodies on the statistical methods appropriate to the analysis of widely varying problems.

The statistical methods developed for handling biological material were found to be specially suitable for dealing with the statistical problems arising in the conduct of military operations, since the observational data relevant to such problems are characterised by a high degree of variability and are in many other ways similar to the data obtained in the course of biological experiment and observation. The accepted statistical measure of the effectiveness of different types of bomb, for example, and of alternative forms of protection against different types of bomb was evolved by the Department a year before war broke out.

It was a natural consequence, therefore, that during the war a great deal of the time of the Department should be devoted to the study of problems not directly connected with the work of Rothamsted. Much of this work arose in connection with urgent war problems, and insofar as many of these problems were of an ephemeral nature, this has interfered with more fundamental and long-term research. On the other hand, contact with widely differing types of problem and different types of material has been fruitful in introducing new methods which are likely to be of value in agricultural research. The need for a closer link between the technical and economic aspects of developmental research has also become apparent, and insofar as the relevant problems are in general quantitative and statistical, they should be the concern of the statistical departments of the research stations.

In addition to work directly connected with investigations of other departments of Rothamsted, and work undertaken for other agricultural institutions, and for the Ministry of Agriculture, the Department in the earlier part of the war carried out work for the Forestry Commission, the Timber Control (Ministry of Supply), and the Home Grown Timber Production Department (Ministry of Supply). This work was mainly concerned with the assessment of timber supplies, and the Department was actively associated both with the 1938-39 and 1941 Censuses of Woodlands. During a great part of the war, Dr. Yates was involved in operational-research problems, first for the Ministry of Home Security and then for the Air Ministry. These investigations were concerned both with protection against air attacks on this country and with the assessment of the effects and planning of air attacks on the enemy. In the course of this work Dr. Yates spent three months in Sicily in the autumn and winter of 1943 and also several months in France,

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Belgium and Germany in 1944-45. Other members of the Department, particularly Mr. Kempthorne, have also assisted in statistical problems arising in operational research.

The only members of the staff who have remained with the Department during the whole of the period have been Dr. F. Yates, Dr. D. A. Boyd, Mr. J. W. Weil, and Miss P. Hurt (now Mrs. Morwood), Secretary. Mr. W. G. Cochran left to take up a post of Assistant Professor in Statistics at Iowa State College, Ames, Iowa, in August, 1939. He was succeeded by Mr. D. J. Finney, who has recently been appointed as Lecturer in the Design and Analysis of Scientific Experiment in the University of Oxford; Mr. Finney left to take up this post in September, 1945. Dr. Boyd, who had worked in the Department for two years (1937-39) as a post-graduate research worker, was appointed to the staff of the Department in October, 1939. Mr. O. Kempthorne joined the Department in July, 1941 from the Ministry of Supply. Mr. M. H. Quenouille was appointed in September, 1944. Mr. F. J. Anscombe and Mr. A. E. Jones joined the Department in November, 1945, Mr. Anscombe from S.R.17, Ministry of Supply and Mr. Jones from Armament Research Department, Ministry of Supply. Mrs. I. Mathison took up an appointment as Supervisor of the Survey of Fertiliser Practice in July, 1941.

The history of the war years would be incomplete without mention of the fact that at the outbreak of war the Galton Laboratory was evacuated to Rothamsted and remained here during the whole course of the war, thus continuing the long association between Professor R. A. Fisher and the Department. Mrs. R. O. Cashen, after doing two years' research work on the effects of rainfall on the permanent grass plots at Rothamsted under Professor Fisher, joined the Department when Professor Fisher left to become the Arthur Balfour Professor of Genetics at Cambridge.

In addition to the above workers there have been a number of workers who have been with the Department for shorter periods during the war. Miss R. Sumpton supervised the computation of the analysis of the National Farm Survey for two years from July, 1943 to August, 1945. Dr. E. C. R. Reeve carried out work on the 1938-39 Census of Woodlands and for the Ministry of Home Security, being with the Department from August, 1940 to December, 1940. Mr. J. S. Gregory took up a temporary post from August, 1943 to September, 1944. Mr. W. L. Stevens transferred from the Galton Laboratory in March, 1941 before taking up a post as Lecturer in Statistics at Coinbra, Portugal, on behalf of the British Council. He is now research statistician to I.C.I. Billingham.

The following voluntary workers and students have worked in the Department during the period 1939-45.

Name	*Location*	*Period of Visit*
R. N. P. Luddington	The United Africa Co., Ltd., West Africa	Aug. 1938–Jan. 1939
Helen N. Turner	Counc. for Sci. & Ind. Res., Australia	Jan. 1939–Aug. 1939
P. A. Loiziedes	Dept. of Agriculture, Greece	April 1939–Aug. 1939
P. N. Sahni	Agric. College, Punjab, India	April 1939–Sept. 1939
G. Polychroniades	Inst. for Plant Breeding, Greece	July 1939
D. E. V. Koch	Dept. of Agriculture, Ceylon	July 1939–Aug. 1939
L. Lebacq	Unilever Ltd., Belgian Congo	July 1939–Aug. 1939
A. F. MacKenzie	Dept. of Agriculture, Sierra Leone	July 1939–Aug. 1939

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Name	*Location*	*Period of Visit*
S. H. Justesen	Afric. Exper. Station, Java	Aug. 1939
P. P. Agarwal	Lucknow, India	Aug. 1939–Sept. 1939
E. J. Williams	Counc. for Sci. & Ind. Res., Australia	Sept. 1939–Mar. 1940
V. G. Panse	Instit. Plant Industry, Central India	Sept. 1939–April 1940
F. Ferguson	United Africa Company, Nigeria	Oct. 1939–Dec. 1939
M. A. Kleczkowski	Poland	Oct. 1939–Mar. 1940
J. Reynolds	England	Oct. 1939–April 1940
A. Sismandis	Dept. of Agron., Tobacco Inst., Greece	Nov. 1939–Dec. 1939
R. A. Aguirre	Nitrate Corporation, Chili	Nov. 1939–Jan. 1940
A. G. Riaz	Agric. Dept., Punjab, India	May 1940–June 1940
B. Lessware	Assam Frontier and Budla Betta Tea Co., Assam	Sept. 1940
T. M. Carey	Cork University, Ireland	Jan. 1943–June 1945
S. Michaelson	Imperial College of Science, London	July 1944–Sept. 1944
M. Bernal	Imperial College of Science, London	July 1944–Sept. 1944
B. Monic	Poland	Sept. 1944–Oct. 1944
T. Chinloy	Dept. of Sci. and Agric., Jamaica	Jan. 1945–Jan. 1946
F. W. Cope	Dept. of Agriculture, Grenada	June 1945–July 1945
M. A. G. Hanschel	Agricultural Dept., Sierra Leone	July 1945–Aug. 1945
C. E. Ford	Rubber Research Scheme, Ceylon	Nov. 1945–Dec. 1945

Work of the Department

The work of the Department can be broadly classified under five heads :

(1) Researches in statistical theory and method.
(2) The planning of experiments and experimental programmes.
(3) Routine statistical analyses of the results of experiments, etc.
(4) Critical statistical analyses of bodies of experimental and observational data.
(5) The planning and analysis of sampling and other surveys.

Individual pieces of research may involve work under more than one of these heads. Thus, work under any one of the last four heads may give rise to problems which require research in statistical theory and method. Equally, an experimental programme may involve work at the planning stage, at the routine analysis stage, and also in the final critical examination of the results. In the subsequent sections of this report researches in statistical theory and method have been grouped together, as has work on surveys, while the various investigations which have required work under one or more of heads 2, 3 and 4 have been grouped under " Special Investigations."

Practically all work under the last four heads is carried out in conjunction with other departments of Rothamsted and with other research institutes. One of the most useful and interesting of the activities of the Department has lain in the preliminary discussions on experimental projects. Research workers inexperienced in the possibilities of modern experimental design frequently fail to realise the advantages which accrue from planning field investigations in a comprehensive manner. Projects are consequently over-simplified, often from a mistaken desire to obtain high accuracy on one particular point, with failure to recognise that this accuracy is of no value if the particular set of conditions postulated by the experimenter does not happen to hold. Planning of experimental programmes demands not only choice of suitable experimental designs, and possibly research into the theory of experimental

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design, but also a careful choice of the factors and combinations of factors to be included in the experiments.

The Department carries out each year a considerable number of routine statistical analyses of the results of replicated experiments, including almost all the field experiments of Rothamsted and its associated centres, and a number of the laboratory and other experiments of the Station. In addition other institutes, both in this country and overseas, from time to time send us the results of experiments which they have found difficulty in analysing themselves : although only general advice is usually asked for, it is more satisfactory, and often quicker, if a worker is in difficulty in the statistical analysis of some experiment, to base such advice on the results of a full analysis. The Department is also frequently asked to advise on sampling methods, and this involves routine calculation in the estimation of sampling errors of new types of material. All this work follows a fairly standard pattern and need not be further discussed in the present report.

Researches in Statistical Theory and Method

As mentioned in the introductory section this aspect of the work of the Department has necessarily been somewhat neglected during the war, and the methods that have been evolved have in the main been developments of already well known principles, designed to deal with the increasingly complex situations to which these principles are being applied. The general principles of statistical analysis evolved in the inter-war period are applicable to a very wide variety of problems, and quite apart from the war, the trend of the work of the Department is likely to lie more and more in the direction of development of new applications of already established principles. Each problem requires its own specialised approach, and one of the troubles in the past has been over-generalised treatment which has taken insufficient account of the many complexities to which each problem is subject.

General

A certain amount of research has been carried out on miscellaneous mathematical statistical problems. Accounts of problems arising in operational research have not yet been published. Published papers on other problems are : (3), which gives an exact test of significance for the largest apparent effect in a replicated experiment containing several factors ; (4), which discusses the problem of estimating the mean and variance and of making tests of significance on statistics arising from very skew distributions ; (5) and (6), which discuss some orthogonal properties of the 4×4, 5×5 and 6×6 Latin squares, which are of value in experimental design ; and (7) which discusses the problem of estimating the error of a ratio.

A table for the estimation of densities of organisms by the dilution method has been calculated by Mr. W. L. Stevens, and was incorporated in the second edition of *Statistical Tables* (1).

An elementary account of the principles of biological statistics will be found in (8).

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Design of experiments

The design of short-term agricultural field experiments had been fairly thoroughly developed before the war. The summary *The Design and Analysis of Factorial Experiments* (F. Yates), published in 1937 by the Imperial Bureau of Soil Science, made available a repertoire of methods adequate for dealing with most problems arising in short-term experiments. During the war years steadily increasing use has been made of these methods. It is now generally recognised—what was by no means the case before the war—that the modern type of factorial design results in more efficient use of experimental resources, and that by permitting the simultaneous investigation of a number of related factors, it enables an understanding of the underlying phenomena to be obtained that was impossible with the old simple type of experiment. Thus, the experiments on organic manures conducted during the last few years by the Chemistry Department, which were designed to give information on the responses to the three main inorganic fertiliser components (N, P, K) in the presence and in the absence of organics, have resulted in a much better understanding of the action of organic fertilisers, since they have permitted the separation of the effects which are attributable to the nutrient components in these fertilisers.

The chief developments of method applicable to short-term experiments have been refinements of techniques of which the principles were already known. Researches on the recovery of inter-block information in incomplete-block designs and lattice squares were completed shortly after the outbreak of the war, and accounts have been published (9, 10). Methods applicable to two-dimensional lattices have been described in a publication of Iowa State College, " The Analysis of Lattice and Triple Lattice Experiments in Corn Varietal Tests. I. Construction and Numerical Analysis. II. Mathematical Theory," by G. M. Cox, R. C. Eckhart and W. G. Cochran. Although originally planned for variety trials involving a large number of varieties, lattice squares have proved very suitable for trials of different types of organic fertilisers, having the advantage over ordinary confounded designs that equal precision is obtained on all comparisons. More recent developments have been the use of half-replicate designs (11), and confounding of sub-plot treatments (12, 13). The latter procedure has proved of great value in the organic-fertiliser trials mentioned above ; each main plot, for example, can be split into four sub-plots, which receive either the treatments *n*, *p*, *k*, *npk*, or the treatments *nil*, *np*, *nk*, *pk*, the three-factor interaction NPK being thus confounded with main plots.

A certain amount of research has been carried out on the design of long-term experiments, e.g., experiments for assessing the residual and cumulative values of manures, the effects of different crop rotations, etc. Most of these researches have been of an *ad hoc* nature to provide designs for specific experiments : a considerable number have been for experiments in the tropics. General systematisation of designs of long-term experiments, corresponding to that already carried out for short-term experiments, still remains to be undertaken, and is one of the most urgent tasks in the field of experimental design.

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The new methods are also capable of being applied, much more widely than they have been in the past, to experiments involving animals, particularly experiments on animal husbandry and animal nutrition, and research is required into these applications.

The new methods of experimental design are now beginning to be widely used in the industrial field, in order to test out modifications in manufacturing processes, etc. While experiments of this nature do not normally come within the province of the Department, it is inevitable that members of the Department should occasionally be consulted on such problems: designs have been worked out from time to time for dealing with very different types of material from those normally met with in agricultural field experiments.

On the analysis side, a method of utilising Hollerith machines for the analysis of factorial experiments of the 2^n type has been evolved (14), and has been successfully applied in the analysis of the 1944 and 1945 Factory Series of Sugar Beet Fertiliser Trials. This method is of particular value to the Department as it smooths out the peak load on the computing staff.

Genetics

In continuation of work carried out when working under Professor R. A. Fisher at the Galton Laboratory, Mr. Finney conducted a series of researches into the mathematical problems of estimation arising in the detection of linkage in human populations, which are characterised by the fact that information is often fragmentary, covers one or two generations only, and is always observational rather than experimental. Several papers have been published on the subject (15-21).

While with the Department, Mr. W. L. Stevens published a note giving exact fiducial limits of expectations, based on small numbers of observations derived from the binomial and Poisson distributions (22). These are applicable to the determination of the accuracy of mutation rates (for which the ordinary standard-error formula is grossly misleading), and to many other analogous problems. An extended set of tables was prepared by him for inclusion in the Second Edition of *Statistical Tables* (1).

Dr. Yates read a paper to the Seventh International Genetical Congress, held in Edinburgh immediately prior to the war, on modern experimental design and its function in plant selection (23).

Biological assay

The foundation of the rigorous statistical treatment of data arising in biological assay and toxicology was laid by Professor Fisher in 1935, in an Appendix to a paper by C. I. Bliss, who was then working at the Galton Laboratory. Since then the Department, in co-operation with the Insecticides Department, has played a very active part in developing statistical methods suitable for use in this field.

The most important problems investigated during the period under review have been the interpretation of toxicity tests of mixtures of poisons (24), the extension of the principles of factorial design to toxicological experiments, (25, 26), and the development

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of methods for allowing for mortality amongst the controls (27). Mr. Finney has completed a text book on the subject (2), and tables suitable for use in laboratories have been included in *Statistical Tables* (1); a table dealing with tests in which there is mortality amongst the controls has been added to the third edition. Other papers published on the subject are (3), (28), (29) and (30).

Sampling

Prior to the war the Department was chiefly concerned with sampling problems arising in agricultural and biological research, such as sampling of agricultural crops for estimation of rate of growth, changes in chemical composition, yield, disease infestation, etc. The estimation of the yield of cereal experiments by sampling for the ratio of grain to total produce is discussed in (32). Since the war, the Department has been involved in many other types of sampling problems and the opportunity has been taken to make a thorough review of the whole of the theory of sampling. A review of the present position has been given in a paper read to the Royal Statistical Society in January, 1946 (31). Dr. Yates is also preparing a book on the subject.

Sampling problems arising in economic surveys and in the analysis of economic material have also been investigated in connection with the Survey of Fertiliser Practice (page 264), and the analysis of the National Farm Survey (page 117). The technique of dealing with sampling errors in large-scale surveys of disease and pest infestation have been worked out in connection with the Wireworm Survey (page 116). The sampling problems arising in this survey are discussed in (50). Sampling problems connected with social surveys entered into a number of the investigations conducted by the Ministry of Home Security.

The problem of estimating the sampling error of systematically spaced samples, such as are often used in forestry surveys, is being investigated. While this investigation is not yet complete, considerable advances have been made, and it is likely to be brought to a successful conclusion during the present year.

Special Investigations

The war gave rise to urgent demands for accurate information on many diverse problems. Such information was required as a basis for immediate administrative action, and when the demand arose, there was usually no time for experimental work, so that it was imperative to make use of whatever material was available.

During the war the Department undertook a number of summaries of experimental material relevant to particular problems. The first of these was the summary of the results of all the fertiliser trials conducted in this country since 1900 which is described elsewhere in this report (page 263).

This investigation revealed two points of general importance in research policy. The first was the value of making critical quantitative reviews from time to time of the whole of the available experimental data on given problems. Such quantitative reviews were found in general to require critical statistical re-examination and synthesis of the relevant results. Previously statistical examinations

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carried out in the Department had been confined (apart from those of modern co-ordinated series of experiments) to the results of particular experiments, such as the classical fields at Rothamsted. In these examinations the results of each experiment had been considered alone without reference to similar experiments elsewhere. It now became clear that consideration of all available experimental results throwing light on some particular problem was often much more profitable, the results of past experiments being used as a quarry to provide information on different points as required.

The second point that emerged was that the summarisation of large bodies of experimental work carried out by many workers, often in different countries, requires time for its efficient execution, quite apart from the fact that the summary, when complete, may result in the conclusion that further experimental work is necessary. Administrators, working usually under urgent pressure of day-to-day demands, cannot be expected to become aware sufficiently early of technical and scientific points on which information will be required in the future. Consequently scientists themselves, particularly in times of rapid change, must co-operate with the administration in determining what problems are likely to become of importance in the future, so that the necessary investigations can be initiated in good time.

Effect of changes in level of feeding of dairy cows on milk production

At the request of the Agricultural Economics Branch of the Cambridge School of Agriculture, the Department co-operated with the Economics Branch in an investigation of the effect of changes in level of feeding of dairy cows on milk production. The questions that gave rise to the investigation were how far feeding stuffs could be economised by stricter rationing of dairy cows, and how far concentrates could be replaced by bulky foods.

In order to determine the most efficient feeding policy, the relationship between food intake and milk output must be known. It was originally hoped that the data collected by the Cambridge Economics Branch on the food consumption and milk outputs of a sample of dairy herds in the eastern counties would be adequate, but it was eventually concluded that the data were not by themselves capable of furnishing certain information on this point. It was therefore decided to review all relevant feeding experiments and make a comprehensive analysis and summary of the results. This investigation is reported in (33). It is well known that as the food intake increases the digestive efficiency of an animal falls off. On the other hand, every animal has a high overhead requirement, which in a dairy cow includes not only the maintenance ration, but also food required during dry periods and food for rearing, etc. This would indicate that it may be advantageous to keep cows at a high productive level, even though this may lead to some digestive inefficiency. The analysis showed that a level of feeding slightly higher than the normal rations given in " Rations for Livestock," gave maximum efficiency in terms of milk production and that while raising the feeding above this level was not likely to result in any great loss of efficiency, feeding rates lower than those given in " Rations for Livestock," resulted in a rapid fall in milk production,

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and a corresponding loss in efficiency. It thus appeared that economies of food were not likely to be effected by more stringent rationing of dairy cows, except at the expense of milk yields. Over-stringent rationing resulting from shortage of foods might result in a very serious reduction in the milk supply without any equivalent saving in food.

Evidence on the part played by bulky foods was also obtained, and it was shown that, provided total energy intake was maintained, substitution of part of the concentrates normally fed to a dairy cow by bulky foods, such as roots or hay on an equal starch-equivalent basis did not influence milk yield. It was also found that in the experiments investigated the starch-equivalent system gave better assessment of the relative energy values of different types of food than did the Danish food-unit (F.E.) system, or the total digestible nutrients (T.D.N.) system.

Changes in level of feeding result not only in changes in milk production, but also in changes in live-weight. These changes complicated the interpretation of the results, particularly of the short-term experiments. Some of the experiments also threw light on protein requirements for milk production. These results, however, have not been fully summarised.

Assessment of the value of ley farming

A start has been made in 1945 on planning an investigation of the economic value to the livestock farmer of temporary grazing leys as compared with old grass. A committee, the Joint Supervisory Committee on Ley Farming, was set up by the Ministry towards the end of 1944, to consider possible ways of securing this information. When the problem was reviewed it was decided that before starting direct experimental work it was essential to ascertain whether any satisfactory technique, other than measurements of liveweight increases and grazing days, could be evolved for assessing the yields of grazed pastures, since the use of animals necessarily involves large plots, and consequently the experiments have to be of a very simple nature, and even so only attain very low accuracy.

The cutting of grass at frequent intervals on small caged plots has been tried out in various parts of the world, but a review of the literature showed that the alternative techniques had not been adequately tested. In view of this, trials to compare various cutting techniques with the performance of the animals themselves were instituted by the Ministry and the Grassland Improvement Station in 1945. One of these was carried out at Rothamsted on the Royal Agricultural Society's trial of the residual value of cake feeding (page 236). The grass-cutting work on this trial was carried out by members of the Statistical and Chemistry Departments, and the statistical analysis of all the trials was performed at Rothamsted. The results of the 1945 trials are promising, and the work is being continued in 1946.

This investigation forms only a small part of the more general problem which may be broadly described as the determination of the agronomic and economic value of ley farming relative to other farming systems. The problem is exceedingly complex, involving agronomic research into methods of establishing leys, the evolution

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of suitable strains of grasses and clovers for varied climatic conditions and grazing requirements, the determination of the fertiliser requirements of a ley-arable rotation, etc., and such general questions as the relative merits of leys and permanent grass for pasture and for hay, and the increase in fertility of arable land attributable to leys. It is naturally the concern of many other research institutes as well as Rothamsted. Until a quantitative answer is obtained to these general questions an economic assessment of the relative value of ley and other systems of farming under any given economic conditions cannot be made.

Investigations on fertility questions are necessarily both involved and slow. Consequently, in spite of their recognised importance, little work has been done during the war, for it was apparent that no information could be obtained which would be of value in increasing agricultural production during the war. Prior to the war the only experiment in this country designed to assess the influence on fertility of the introduction of long leys into arable farming was the Woburn experiment described elsewhere in the report (p. 256). This experiment illustrates the lengthy nature of all such investigations : although started in 1938, the first cycle will only be complete in 1946. The fact that the war has interrupted the laying down of similar experiments at other centres makes the present need all the more urgent. They should have high priority in the programmes of the new experimental farms to be established under the National Advisory Services.

Other investigations

Dr. Boyd carried out a statistical examination of 36 years' results of the Saxmundham Rotation Experiment, studying both the responses to fertilisers and the influence of meteorological factors (40). Mrs. Cashen (Mrs. Tysser), working under Professor Fisher, investigated the effect of rainfall on the yields and botanical composition of hay from the Park Grass Plots at Rothamsted (41). Dr. Carey made an investigation of the fertiliser requirements of sugar cane, including a summary of the results of all available fertiliser experiments on this crop (42). All three workers were awarded a Ph.D. at London University.

The accounts of various small investigations which have been carried out during the last seven years are described in the abstracts to papers (34)-(39) and (43)-(47). Certain other investigations have been made of which the results are not yet published.

Trials to assess the value of the resazurin and methylene-blue tests as measures of the keeping quality of milk were instituted in 1944 by the Ministry acting in conjunction with the Conference of Advisory Bacteriologists. The planning and statistical analysis of these trials have been supervised by this Department. The statistical work has been carried out partly at Hove, and partly at Rothamsted. The Department has co-operated in preparing two reports on the results of the trials.

Surveys

During the war the importance of obtaining accurate and reliable information on farming conditions, and on the actual agricultural

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practices of different types of farmers was increasingly realised. Such information is of importance both to the administration in planning the utilisation of scarce resources, development of rationing schemes, etc., and to those engaged in the planning of research and in the dissemination of established scientific and technical knowledge. The subject is fully discussed in (48).

Information of this type can often only be obtained by special surveys of agricultural conditions and practices. The Department has been increasingly consulted on the planning and analysis of such surveys, particularly in connection with the sampling problems that arise in surveys covering only a sample of all farms or fields, or which involve the sampling of individual fields. On the subject of crop estimation and forecasting, on which a good deal of work had been carried out before the war, advice and assistance was given from time to time to the Ministries concerned with wartime estimation problems. The sampling observations on the growth of wheat conducted in the years 1933-1939 at several centres under the Agricultural Meteorological Scheme of the Ministry were abandoned owing to pressure of more urgent war work, but certain tests on the feasibility of using eye estimation for estimating the yields of cereal crops were carried out on the wheat crop in Hertfordshire in the years 1940 and 1941. Mention of this work will be found in (48).

In addition to advisory work the Department has been more closely concerned with three major pieces of survey work; the Survey of Fertiliser Practice, described elsewhere in the report (page 264), the Wireworm Survey, and the National Farm Survey.

The Wireworm Survey

This survey was instituted because of the importance of the wireworm problem under war conditions, when large amounts of old grass were turned over to arable cropping. Its primary object was to evolve methods suitable for assessing wireworm infestation of particular fields, so that advice could be given to farmers on cropping, preventive measures, etc. The material collected also provided a good deal of general information on the wireworm problem.

The survey work was carried out by the Advisory Entomologists acting under the direction of the Plant Pathological Laboratory of the Ministry. The Department gave statistical advice to the Plant Pathological Laboratory on the conduct of the survey, and Mr. Finney played a large part in the drafting of the various reports.

On the statistical side, the survey involved a good deal of preliminary work in the investigation of the errors involved in the sampling of individual fields, and in the evolution of the most suitable methods of sampling. This aspect is discussed in (49) and (50).

In addition, the whole of the statistical side of the reduction and examination of the results was for several years concentrated at Rothamsted, and this involved a very considerable amount of numerical work.

The results of the survey have been reported in a Ministry of Agriculture Bulletin (52).

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NATIONAL FARM SURVEY

During the year 1941-42, the Ministry, acting through the County War Executive Committees, carried out a qualitative survey of all farms of over five acres in England and Wales. The aims and objects of the survey were reported in the Press at the time. The survey covered such aspects as tenure, condition of farm, incidence of insect pests, quality of farming, supply of electricity and water, etc., and included a map record of all farm boundaries. Owing to the labour situation, the analysis on a national basis of the results of this survey by the Ministry's Statistical Department presented serious difficulties, and the Ministry therefore made use of the assistance of Rothamsted. The analysis was carried out by means of Hollerith punched-card equipment, and the numerical work at Rothamsted consisted of summarising the tables produced by the tabulating machines. This work was of a routine character, and a special team of part-time computers was used.

The survey has given the Department valuable experience in the use of Hollerith machinery on the analysis of this type of material, and as a result methods of utilising this machinery have been considerably developed. The data of the survey and of the related June 4th Returns also presented points of general interest on which further investigations have been carried out.

A full report on the survey has been published by the Ministry, (*The National Farm Survey, a Summary Report*, Ministry of Agriculture, H.M.S.O., 1946).

PUBLICATIONS

BOOKS

1. FISHER, R. A. and YATES, F. 1946. *Statistical Tables for Biological Agricultural and Medical Research. 1st Edition*, 1938 ; *2nd Edition*, 1943 ; *3rd Edition*, 1946. Oliver and Boyd, Edinburgh. (In the press.)

These tables have been designed to give a collection under one cover of all those tables that are normally required by the agricultural and biological statistician. In addition to the tables already published in *Statistical Methods for Research Workers* and elsewhere, various new tables have been specially computed for the volume by members of the Statistical Department and of the Galton Laboratory. Opportunity has been taken to add additional material in each new edition.

2. FINNEY, D. J. 1946. *Probit Analysis. A Statistical Treatment of the Sigmoid Response Curve*. Cambridge University Press. (In the press.)

This is a practical working text book designed to give the biological statistician, previously unfamiliar with the subject of probit analysis, a complete account of the subject, including the most recent developments.

1. RESEARCHES IN THEORY AND METHOD

(*a*) *General*

3. FINNEY, D. J. 1941. *The joint distribution of variance ratios based on a common error mean square*. Ann. Eug., **7**, 136-140.

The paper gives the probability distribution of the ratio of the largest of a number of mean squares, all based on the same number of degrees of freedom, to an independent " error " mean square. The computation of exact significance levels is a lengthy process, but the approximation resulting from an assumption of complete independence of the ratios is satisfactory providing that the error degrees of freedom are sufficiently numerous. The determination of significance levels for the least of the variance ratios is arithmetically much simpler, and the similar approximation very satisfactory.

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4. FINNEY, D. J. 1941. *On the distribution of a variate whose logarithm is normally distributed.* Suppl. J. Roy. Stat. Soc., **7**, 155-161.

Formulae have been obtained for efficient estimates of the mean and variance of a sample of a population of which the logarithm of the variate is normally distributed. As the exact expressions are not very suitable for arithmetical computation, approximations are developed which may be used for moderately large samples.

5. FINNEY, D. J. 1945. *Some orthogonal properties of the 4 by 4 and 6 by 6 Latin squares.* Ann. Eug., **12**, 213-219.

Though there are no 6 by 6 Graeco-Latin squares, it is possible to partition 6 by 6 Latin squares orthogonally but less completely. The paper discusses these partitions and gives examples for use in experimental design. The existence of partitions satisfying various more stringent conditions is noted. All 4 by 4 Latin squares can be partitioned, in six different ways, into two sets of eight cells satisfying similar conditions, though only one-quarter of these squares have Graeco-Latin solutions ; these partitions also are tabulated.

6. FINNEY, D. J. 1946. *5 by 5 Latin squares.* Ann. Eug. **13**, 1-3.

All orthogonal partitions of the 5 by 5 Latin squares have been determined, and the implications of the results in experimental design are discussed.

7. COCHRAN, W. G. 1940. *The validity of an approximate formula for the variance of a ratio.* (Appendix.) J. Agric. Sci., **30**, 273-275.

The validity of the usual approximate formula for calculating the variance of a ratio is briefly discussed.

7A. KEMPTHORNE, O. 1944. *Comments on the note "On a theorem concerning sampling."* J. Roy. Stat. Soc., **107**, 58.

8. KEMPTHORNE, O. 1945. *Statistics in biology.* Biol. and Human Affairs, **10**, No. 3, 1-8.

(*b*) *Experimental design and analysis*

9. YATES, F. 1940. *Lattice squares.* J. Agri. Sci., **30**, 672-687.

The paper describes a new method of analysing the results of experiments arranged in lattice (quasi-Latin) square designs, utilising the information contained in the inter-row and inter-column comparisons. The methods of computation are described in detail, and are illustrated by examples. With this modification, lattice squares will always give results which are as accurate as, or more accurate than, ordinary randomised blocks.

10. YATES, F. 1940. *The recovery of inter-block information in balanced incomplete block designs.* Ann. Eug., **10**, 317-325.

The method of recovering inter-block information in incomplete block designs is described and is illustrated by numerical examples.

11. FINNEY, D. J. 1945. *The fractional replication of factorial arrangements.* Ann. Eug., **12**, 291-301.

The relationship of schemes for factorial experiments to the elementary theory of prime power groups has been discussed with particular reference to 2^n and 3^n factorial arrangements. It is shown that fractional replication of these arrangements is permissible provided that the experimenter does not require information on high order interactions. A numerical example has been given for half-replication of a 2^n arrangement.

12. FINNEY, D. J. 1946. *Recent developments in the design of field experiments. 1. Split-plot confounding.* J. Agric. Sci., **36**, 56-62.

The design of experiments in which some of the interactions of the sub-plot treatments are confounded with the main plots is discussed.

13. FINNEY, D. J. 1946. *Recent developments in the design of field experiments. 2. Unbalanced split-plot confounding.* J. Agric. Sci., **36**, 63-68.

Further extensions of split-plot confounding to designs in which the number of variants of the different factors is such that complete balance is not possible, are described.

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14. KEMPTHORNE, O. 1946. *The analysis of a series of experiments by the use of punched cards.* Suppl. J. Roy. Stat. Soc. (In the press.)

The analysis of the sugar beet series of fertiliser trials which are of 2^5 type of factorial design by means of Hollerith punched cards is described. Possible extensions to other types of experiment are briefly discussed.

(c) Genetics

15. FINNEY, D. J. 1940. *The detection of linkage.* Ann. Eug., **10**, 171-214.

16. FINNEY, D. J. 1941. *The detection of linkage. 2. Further mating types; Scoring of Boyd's data.* Ann. Eug., **11**, 10-30.

17. FINNEY, D. J. 1941. *The detection of linkage. 3. Incomplete parental testing.* Ann. Eug., **11**, 115-135.

18. FINNEY, D. J. 1942. *The detection of linkage. 4. Lack of parental records and the use of empirical estimates of information.* J. Hered., **33**, No. 4.

19. FINNEY, D. J. 1942. *The detection of linkage. 5. Supplementary tables.* Ann. Eug., **11**, 224-232.

20. FINNEY, D. J. 1942. *The detection of linkage. 6. The loss of information from incompleteness of parental records.* Ann. Eug., **11**, 233-244.

21. FINNEY, D. J. 1943. *The detection of linkage. 7. Combination of data from matings of known and unknown phase.* Ann. Eug., **12**, 31-43.

In this series of papers methods are developed for making efficient tests of linkage from family records of the type usually encountered in human studies of genetics. These methods are based on scoring procedures of the type originally introduced by Professor R. A. Fisher.

22. STEVENS, W. L. 1942. *Accuracy of mutation rates.* J. Gen., **43**, 301-307.

The use of the standard error of estimates of mutation rates, and other small proprotions, is shown to be highly erroneous. A table is provided for rapidly making the exact tests of significance.

23. YATES, F. 1940. *Modern experimental design and its function in plant selection.* Emp. J. Exp. Agric., **8**, 223-230.

The paper gives a summary of the various experimental designs of the quasi-factorial, balanced incomplete block, and lattice square type, that have been introduced to test large numbers of varieties, while eliminating fertility differences as far as possible. The advantage of including a large number of varieties in field trials at the cost of some reduction in the accuracy of individual comparisons, in order to reduce the chance of some particularly good variety being rejected without trial, is stressed.

(d) Biological assay

24. FINNEY, D. J. 1942. *The analysis of toxicity tests on mixtures of poisons.* Ann. Appl. Biol., **29**, 82-94.

The interpretation of the results of toxicity tests on mixtures of poisons is fully discussed, new methods are developed for dealing with independent, similar and synergistic action, and examples of their application are given.

25. FINNEY, D. J. 1942. *Examples of the planning and interpretation of toxicity tests involving more than one factor.* Ann. Appl. Biol., **29**, 330-332.

The paper gives a brief review of toxicity tests which have included combinations of different techniques of applying poisons, or which have tested mixtures of poisons.

26. FINNEY, D. J. 1943. *The statistical treatment of toxicological data relating to more than one dosage factor.* Ann. Appl. Biol., **30**, 71-79.

The extension of factorial design to toxicological experiments involves new problems of analysis, which are discussed in this paper. It is shown that

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probit regression planes can be fitted in a manner analogous to that used for regression lines. The arithmetical procedure of fitting is illustrated by an example and tests are given for heterogeneity and parallelism. Numerical examples used by Bliss are also discussed in relation to the methods of fitting and forms of equation given in this paper.

A more general class of equations is introduced for use when the probit mortality is linearly related to each dosage factor separately, but the individual effects are not additive.

27. FINNEY, D. J. 1944. *The application of the probit method to toxicity test data adjusted for mortality in the controls.* Ann. Appl. Biol., **31**, 68-74.

Methods of dealing with data in which the untreated controls are subject to a mortality rate are developed, and the necessary tables are presented.

28. FINNEY, D. J. 1944. *The application of probit analysis to the results of mental tests.* Psychometrika, **9**, 31-39.

The paper contains an outline of the method of probit analysis and an illustration of the most convenient form of computations for use in analyses of psychometric data.

29. FINNEY, D. J. 1944. *Mathematics of biological assay.* Nature, **153**, 284.

The applicability of the four-point assay is discussed.

30. FINNEY, D. J. 1945. *The microbiological assay of vitamins : the estimate and its precision.* Quart. J. Pharmac., **18**, 77-82.

The estimation of relative potency by the method of maximum likelihood is developed for the case, arising in certain micro-biological assays. in which the response shows a linear relationship with the dose and the regression lines for the two proportions are constrained to give the same value at zero dose.

(*e*) *Sampling and sampling surveys*

31. YATES, F. 1946. *A review of recent statistical developments in sampling and sampling surveys.* J. Roy. Stat. Soc., **109**, 12-30.

The paper gives a review of the present position of sampling theory and practice with an outline of the contributions made by biological and agricultural statistics. A summary of sampling methods and the appropriate methods of forming estimates and calculating sampling errors is given, including a discussion of methods of improving the accuracy by adjustment of the results. The use of ratios or percentages and the use of a variable sampling fraction including the problems arising in the estimation of error when quasi random or systematic sampling is used are also discussed. The sampling problems arising in social surveys and the planning of sampling enquiries, are reviewed.

32. COCHRAN, W. G. 1940. *The estimation of the yields of cereal experiments by sampling for the ratio of grain to total produce.* J. Agric. Sci., **30**, 262-275.

One possible method of determining the yields of cereal experiments is to weigh the total produce on each plot and to take samples for estimating the ratio of grain to total produce, either from the sheaves or from the standing crop. The paper discusses the sampling errors of this method, which is shown to require about $\frac{1}{4}$ of the number of samples that would be required in sampling directly from the standing crop. Grab sampling from the sheaves, though slightly biased, is otherwise satisfactory.

2. STATISTICAL ANALYSES OF COLLECTIONS OF EXPERIMENTAL AND OBSERVATIONAL DATA

33. YATES, F., BOYD, D. A. and PETTIT, G. H. N. 1942. *Influence of changes in level of feeding on milk production.* J. Agric. Sci., **32**, 428-456.

The influence upon milk production of changes in level of feeding and in proportion of bulky foods has been investigated using all available experimental material.

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The experimental results show that increases in level of feeding, to rates well in excess of conventional English standards, are capable of giving substantial increases in milk production.

It is shown that physiological efficiency falls off as food intake is increased. A curve representing physiological efficiency has been constructed by taking account of changes in live weight as well as changes in yield of milk.

The question of the most efficient feeding rate is discussed. Owing to the high overhead and maintenance requirements of the cow, a fairly high level of feeding of about 2 ·8 lb. starch equivalent per gallon of milk, gives maximum efficiency. This is so in spite of lower physiological efficiency at high levels of feeding and additional loss resulting from the utilisation of part of the food supply to increase body weight. This feeding rate approximates to the rate which would have given maximum profit at 1941-2 prices if food could have been freely bought and sold. There is thus no economic inducement to feed at excessive rates, and the chief danger appears to be under-feeding, due either to too stringent rationing or to an attempt to keep too many animals in times of general food stringency.

The feeding of bulky foods alone may reduce yield owing to limitation of total energy intake. Provided total energy intake is maintained, substitution of part of the concentrate ration by bulky foods such as roots or hay, on an equal starch equivalent basis, does not influence milk yield.

The results of these experiments show that the starch equivalent system gives a better assessment of the relative energy values of different foods than does the food unit (F.E.) system or the total digestible nutrients (T.D.N.) system.

34. FINNEY, D. J. 1940. *The Little Hoos field experiment on the residual values of certain manures.* Emp. J. Exp. Agric., **8**, 111-125.

The paper contains an analysis of the results of the Little Hoos field experiment at Rothamsted (which ran from 1904-1926) on the residual values of various organic manures and forms of phosphate applied to a four-course rotation. The design of the experiment was such that no very definite conclusions could be drawn, but the experimental results appeared to show residual effects of dung up to three years from their application, but no residual effects for guano, shoddy or rape dust. Basic slag showed more consistent residual effects than superphosphate or bone meal.

35. TURNER, HELEN N. 1939. *The residual effects of organic fertilisers : A preliminary report on the Rothamsted four-course rotation experiment.* Emp. J. Exp. Agric., **7**, 343-349.

The paper gives a preliminary analysis of the first 8 years' results of the Rothamsted four-course rotation experiment on the residual effects of organic fertilisers.

36. GARNER, H. V. and WEIL, J. W. 1940. *The cultivation of malting barley in England.* Emp. J. Exp. Agric., **8**, 65-79.

The agricultural data and grading of some 1,200 samples of English malting barley are set out and discussed. Classification by differences showed marked differences in quality in different localities. Autumn sowing usually produced barley particularly superior in quality, but inferior in yield to the spring sown barleys. Samples sown early in the spring tended to be better in quality than those sown later in the season. The heavier class of soil tended to produce better barley in dry years and vice versa.

37. SAHNI, P. N. 1941. *The relation of drainage to rainfall and other meteorological factors.* J. Agric. Sci., **31**, 110-115.

Following the earlier work of CROWTHER and KOSHAL, the drainage from the Rothamsted 20 in. drain gauge has been related to rainfall and other meteorological factors.

38. FINNEY, D. J. 1941. *The relationship of plant number and yield in sugar beet and mangolds.* Emp. J. Exp. Agric., **9**, 57-64.

Examination of the relationship between plant density and yield in four widely different sets of experiments on sugar beet and mangolds indicates that, with a normal plant population, any elimination of roots may be expected to be accompanied by about half the proportionate loss in yield.

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39. GARNER, H. V. and WEIL, J. W. 1939. *The standard errors of field plots at Rothamsted and outside centres.* Emp. J. Exp. Agric., **7**, 369-379.

The standard errors per plot obtained in some 1,200 analyses relating to data from modern replicated experiments carried out at Rothamsted, Woburn, and outside centres during 1925-38 are recorded and classified.

40. BOYD, D. A. 1940. *The influence of meteorological factors on arable crop yields, based on an examination of the results of the Saxmundham rotation experiment.* (Thesis for Ph.D. degree in the University of London.)

The results of this experiment from 1900 to 1937 are summarised and discussed, and the influence of meteorological factors is investigated.

41. CASHEN, R. O. 1944. *The effect of rainfall and associated weather on manurially treated permanent grassland as demonstrated by manurial experiments carried out since* 1856 *on the grass plots in Rothamsted Park.* (Thesis for Ph.D. degree in the University of London.)

The results of an examination of the effect of rainfall on the yields and chemical composition of the hay of the Park grass plots, Rothamsted, is reported.

42. CAREY, T. M. 1945. *Fertiliser requirements of sugar cane.* (Thesis for Ph.D. degree in the University of London.)

An investigation of the fertiliser requirements of sugar cane has been made, with a summary of all available fertiliser experiments on this crop.

See also: Department of Entomology, Refs. 21, 22, 30, 34; *Bee Department*, Refs. 14, 15; *War-time Fertiliser Policy*, Ref. 1.

3. SURVEYS

(*a*) *General*

48. YATES, F. 1943. *Methods and purposes of agricultutal surveys.* J. Roy. Soc. Arts, No. 4641.

This paper gives a review of the current developments in agricultural surveys illustrated by examples of recently executed surveys.

(*b*) *Wireworm survey*

49. FINNEY, D. J. 1941. *Wireworm populations and their effect on crops.* Ann. Appl. Biol., **28**, 282-295.

The results of sample determinations of wireworm populations carried out by the Advisory Entomologists in connection with the Wireworm Survey in 1939-40 are reviewed. There was a very marked decrease in infestation from south to north of the country. The adequacy of the standard sampling technique employed (20 in. cylindrical cores 4 in. in diameter) is discussed, and the effects of wireworm infestation on the subsequent crops are analysed.

50. YATES, F. and FINNEY, D. J. 1942. *Statistical problems in field sampling for wireworms.* Ann. Appl. Biol., **29**, 156-167.

Grass fields have shown very much higher populations in the south-east and midland areas than in the north and west both in 1939-40 and 1940-41. In spite of a reduction in 1940-41 in the lower size limit of the larvae to be counted in the samples, populations in this latter season tended to be lower than in 1939-40. Arable fields sampled in 1940-41 gave populations generally lower than grass fields, and the geographical trend was less noticeable.

A general summary of the principles underlying field sampling, with particular reference to the taking of soil samples for the estimation of wireworm population, has been given.

51. FINNEY, D. J. 1943. *Recent developments in the wireworm survey.* Agric. Prog., **8**, 36-38.

Further results on the size of wireworm populations and damage to crops are briefly recorded.

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52. 1944. *Wireworms and food production—a wireworm survey of England and Wales* (1939-1942). (Report from the Advisory Entomologists Conference.) Min. Agric. Bull., **128.**

This bulletin contains a full report of the results of the Wireworm Survey. Subjects discussed are : the technique of wireworm sampling, the distribution of *agriotes* populations in England and Wales, the influence of husbandry on wireworm populations, the influence of wireworms on the establishment and success of arable crops. Recommendations are made for mitigating damage due to wireworms.

(*c*) *Survey of fertiliser practice*

53. YATES, F., BOYD, D. A., and MATHISON, I. *The manuring of farm crops : Some results of a survey of fertiliser practice in England.* Emp. J. Exp. Agric., **12,** 164-176.

The report presents some of the main findings ot the survey which have immediate relevance from the point of view of improving the use of fertilisers. The report covers counties in the Advisory Provinces of Cambridge, Bristol and Leeds, and in the main relates to the manuring of the 1942 crops.

Generally speaking, districts which have always depended mainly on arable cropping use adequate amounts of fertilisers, and make satisfactory differentiation between the needs of different crops. Even in these districts, however, the special needs of newly ploughed-out grassland have not been fully recognised, and crops tend to be manured without regard to the land on which they are grown.

Farmers in the dairy and cattle-rearing districts of the West of England and Yorkshire, who before the war had had little experience of arable farming, are much less " fertiliser-conscious " than farmers in the eastern arable counties, and make insufficient use of fertilisers, even on old arable land. For example, the manuring of root crops is frequently ill balanced and inadequate in the western counties ; although very large supplies of farmyard manure are available, almost one-third of the root acreage received none, and many fields received no phosphate or no nitrogen. Even within the chief arable districts there were many farms mainly in grass before the war (e.g., in West Bedford and South Essex), which make less effective use of fertilisers than their neighbours with greater experience of arable farming.

As a consequence, the use of lime and phosphate on new arable land has been quite inadequate over most of the surveyed area. The survey has confirmed (what has already been frequently emphasised) that new arable land is generally both much more acid and much more deficient in phosphate than old arable, but it is apparent that except in one or two districts this land has received less lime and less phosphate in recent years than has the old arable land.

The failure to recognise the function ot farmyard manure as a source of phosphate, and more particularly potash, is also striking. The survey shows that farmers require encouragement to use mixtures with a lower proportion of phosphate and potash where farmyard manure is also given.

The failure to distinguish clearly between the different action of the various plant nutrients has also led to an inadequate use of nitrogen on cereals grown after roots, presumably owing to the belief that the heavy manuring of the roots will have led to sufficient stored-up fertility. Certainly in those cases where only inorganic nitrogen has been used to manure the root crop, there is every reason to give a reasonable nitrogenous dressing to the following corn. There are also wide differences from farm to farm in the use of nitrogen on cereals, and it is clear that some farmers, at least, could profitably make greater use of this fertiliser. Only half the acreage of cereals in the surveyed provinces actually received nitrogen, and it is unlikely that a higher proportion receives nitrogen in the country as a whole.

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