Journal of the History of Biology (2015) 48:301–335
DOI 10.1007/s10739-014-9394-z

The Emergence of Modern Statistics in Agricultural Science: Analysis of Variance, Experimental Design and the Reshaping of Research at Rothamsted Experimental Station, 1919–1933

GIUDITTA PAROLINI
Technische Universität Berlin and Berliner Zentrum für Wissensgeschichte
Berlin
Germany

Institut für Philosophie, Literatur-, Wissenschafts- und Technikgeschichte
Technische Universität Berlin
Sekretariat H72
Straße des 17 Juni, 135
10623 Berlin
Germany
E-mail: giudittaparolini@gmail.com

Abstract. During the twentieth century statistical methods have transformed research in the experimental and social sciences. Qualitative evidence has largely been replaced by quantitative results and the tools of statistical inference have helped foster a new ideal of objectivity in scientific knowledge. The paper will investigate this transformation by considering the genesis of analysis of variance and experimental design, statistical methods nowadays taught in every elementary course of statistics for the experimental and social sciences. These methods were developed by the mathematician and geneticist R. A. Fisher during the 1920s, while he was working at Rothamsted Experimental Station, where agricultural research was in turn reshaped by Fisher's methods. Analysis of variance and experimental design required new practices and instruments in field and laboratory research, and imposed a redistribution of expertise among statisticians, experimental scientists and the farm staff. On the other hand the use of statistical methods in agricultural science called for a systematization of information management and made computing an activity integral to the experimental research done at Rothamsted, permanently integrating the statisticians' tools and expertise into the station research programme. Fisher's statistical methods did not remain confined within agricultural research and by the end of the 1950s they had come to stay in psychology, sociology, education, chemistry, medicine, engineering, economics, quality control, just to mention a few of the disciplines which adopted them.

Keywords: Agriculture, Archives, Computing, Experimentation, R. A. Fisher, Statistics

Statistical methods have transformed experimental practices in the biological, medical, and social sciences during the twentieth century. Qualitative evidence has largely been replaced by quantitative results and the tools of statistical inference have helped foster a new ideal of objectivity in scientific knowledge (Gigerenzer et al., 1989; Porter, 1996, Chap. 8).

Increasingly engaged as consultants in experimental research as well as in business and administration, statisticians have represented themselves as the ‘‘backroom boys’’ (Fisher, 1953, p. 2) or the ones who ‘‘get to play in everyone’s backyard’’ (Tukey quoted in Upton and Cook, 2008) and have found a space for their expertise in institutions devoted to biology, medicine and psychology, where once the experimental scientist alone was welcome.

Applied statistics has become an integral component of experimentation in the twentieth century and, vice versa, statistical methods have been developed in response to experimental needs. But making room for new people and new skills has not been enough. Statisticians have also claimed a role in experimental research for the tools of their trade – computing instruments and information technologies – helping to make number crunching and data management essential to experimentation.

As argued by Edward Higgs and JoAnne Yates (Higgs, 1996; Yates, 2008), investigating the history of applied statistics, therefore, requires us to unravel the complex interaction of mathematical tools, workplace practices, institutional organization, and technological developments in computing and information management, and account for how these elements have mutually shaped each other. While Higgs and Yates have addressed statistics, respectively, in the context of the Census of England and Wales and of U.S. insurance companies, such an inclusive effort has yet to be tried systematically for the history of statistics in experimental research.

This paper will investigate a case study in agricultural research, which was one of the principal contexts for the development of statistical theory during the 1920s and 1930s, one which has thus far received little historical attention.[1] It will examine analysis of variance and experimental design, the statistical methods developed in the 1920s by the mathematician and geneticist Ronald Aylmer Fisher. These statis-

[1] The few sources available on the role played by statistics in agricultural research between nineteenth and twentieth century are: Eden, 1935, pp. 63–69, 131–149; Crowther, 1936, pp. 54–81; Cochran, 1976; Gigerenzer et al., 1989, pp. 70–106; Swijtink, 1994; Hall, 2002, pp. 34–49; 2007. In general it is the whole history of agricultural science that has so far been neglected. For an historiographical assessment see Harwood, 2005, pp. 26–28.

tical tools were born at Rothamsted Experimental Station (RES), a landmark institution for British agricultural research, and used at first in both the planning and analysis of field experiments and in the laboratory research conducted there. In only a few short years, however, they became very popular in and beyond agricultural science and they are nowadays taught in every elementary course of statistics for students of the experimental and social sciences.

Ronald Fisher was the first statistician hired by RES. He began to work at the station in 1919 and was the founding father of the institution's statistics department, which he managed until 1933. Fisher left a permanent imprint on agricultural statistics, but surprisingly, his involvement in agricultural research has received little attention.[2] Rather, Fisher has been portrayed as an outstanding mathematician by his fellow statisticians and by his main biographer, the daughter Joan, while historians have mainly investigated Fisher as a founding father of population genetics and an active eugenicist, as emphasized, for instance, by Donald Mackenzie.[3]

The present historical account uncovers a very different dimension of Fisher presenting him as a consultant of the Rothamsted experimental scientists and framing his statistical methods in the research practices adopted at the agricultural station. Unlike Mackenzie, in fact, it is claimed that the analysis of variance was not the outcome of Fisher's eugenics concerns, but, together with experimental design, was developed in response to the experimental problems posed by the research done at Rothamsted, eventually becoming crucial in the management of the station's research programme.[4]

It is argued that Fisher's methods reshaped experimental life at RES. On the one hand statistics required new experimental practices and instruments in field and laboratory research, and imposed a redistribution of expertise among statisticians, experimental scientists and the

[2] One notable exception is N. S. Hall's work on Fisher (Hall 2002, 2007). See also Street, 1990.

[3] A comprehensive biography of R. A. Fisher is Fisher Box, 1978. Assessments/celebrations of Fisher's work written by his fellow statisticians are, for instance, Salvage, 1976; Hald, 1998, 2007; Lehman, 2011. On the historians' assessment of Fisher as a contributor to population genetics and active eugenicist see Mackenzie, 1981, Chap. 8; Mazumdar, 2011, Chap. 3; Provine, 2001, pp. 140–154.

[4] Mackenzie, 1981 is ambivalent over the evaluation of Fisher's statistical work. On the one hand he claims that "Fisher's work in biology was strongly connected to his involvement in the eugenics movement," but "what is novel in Fisher's statistical theory must, in general, be sought elsewhere" (p. 188), on the other hand he does not hesitate to link the development of the analysis of variance to Fisher's work in eugenics (p. 211).

farm staff. On the other hand the use of statistical methods in agricultural science called for a systematization of information management and made computing an activity integral to the experimental research done at the station, permanently integrating the statisticians' tools and expertise into the station's research programme.

In addressing the origins of analysis of variance and experimental design in agricultural science the paper offers a novel insight into the historical development of present day quantitative research. In particular, the paper points out that the emergence of statistics in the soft sciences cannot be addressed in terms of mere theoretical change or focusing only on the role acquired by the "inference experts," but rather as an overall reshaping of scientific tools and practices prompted in the case of agricultural science, by a quest for precision inspired by economic reasons.[5] Experimentation, where tools and practices are intertwined, offers a vantage point to address such transformation.

Between Field and Laboratory: Agricultural Research at Rothamsted Experimental Station

The experimental station of Rothamsted, now called Rothamsted Research, was set up in 1843 by John Bennet Lawes, English squire, amateur chemist and successful businessman in the fertilizer industry. At the mid of the nineteenth century Lawes sponsored a series of long-term experiments on crops and fertilizers in the fields of his private estate located in the village of Harpenden, Hertfordshire. Using the results of these experiments, Lawes, in association with the professional chemist Joseph Henry Gilbert, "attempted to explain how things worked by the application of skills or techniques not generally available to farmers in order to benefit the community in general" (Brassley, 1995, p. 467).[6] Gilbert was a pupil of the German chemist Justus von Liebig and the agricultural science practiced by Lawes and Gilbert relied heavily on analytical chemistry for determining the composition of soil and crop samples.[7]

[5] Gigerenzer et al., 1989 devote a whole chapter (No. 3) to inference experts. On the economic dimension linked to the use of statistics in agricultural science see the last section of the paper.

[6] On the history of RES see Russell, 1966, pp. 88–107, pp. 143–175, pp. 232–243, pp. 289–332. On Lawes see Thompson, 2004–2008. On Gilbert see Clarke, 2004–2008.

[7] On Liebig's contributions to agricultural science (from a U.S. perspective) see Rossiter, 1975.

Alfred Daniel Hall and Edward John Russell, respectively the second (1902–1912) and third (1912–1943) directors of the station, instead held a broader idea of agricultural science and promoted at Rothamsted new disciplines such as botany and entomology. In the 1920s, when analysis of variance and experimental design were developed, RES had four main departments – biological, chemical, physical and statistical – and facilities that included a farm and experimental fields (RES, 1921, pp. 4–5).[8] The scope of the research activity, however, was still "in the main restricted to the soil and the growing crop," as it had been with Lawes and Gilbert (RES, undated, p. 1). The long-term experiments initiated by the Rothamsted founding fathers were carried on and new annual trials on crops and fertilizers were planned from year to year.[9]

At Rothamsted the departments and the farm were both distinct and interrelated experimental contexts, in continuity with the tradition established at the station since the nineteenth century, of an agricultural science that involved both field trials and laboratory investigations. Crop and soil samples were brought into the biological, chemical and physical departments for examination, while a field laboratory was built in the experimental fields for closer scrutiny of nature.[10] In this two-way relationship between field and laboratory the desideratum that accompanied the opening of the Rothamsted statistics department was to align field practice to laboratory standards, while preserving the intrinsic complexity of field experiments (RES, 1921, p. 8). Unlike laboratory research in which conditions can be controlled and investigations focus on one variable at a time, field experiments in agricultural science deal with environmental factors, such as soil fertility and weather conditions, which mutually interact and can heavily affect the results of a trial from season to season.

In order to assess the influence of these factors and to work out reliable suggestions for farmers, agricultural science developed *ad hoc* experimental practices, notably the use of comparative and repeated (in time and space) field trials. These experimental techniques were already in use in the eighteenth century, as proved by the work on wheat

[8] Both A. D. Hall and E. J. Russell were key figures in the development of British agricultural science during the first half of the twentieth century. More information on them can be found in Brassley, 2004–2008 and Pirie, 2004–2008.

[9] On the history of the long-term experiments at Rothamsted see Johnston, 1994, pp. 9–37.

[10] The field laboratory was built in the mid 1920s to monitor the growth of crops (RES, 1927, p. 27).

husbandry of Arthur Young, author of an extensive treatise on experimental agriculture.[11]

At first the comparisons in agricultural science were visual and qualitative, but since the nineteenth century, chemistry promoted a "desire for precision" and it was strongly recommended that the samples collected in field trials were analysed for their chemical and physical composition, weighted and measured, and the results carefully recorded.[12]

By the middle of the nineteenth century it was also explicitly recommended – for instance by the chemist James Johnston – to pay attention to the arrangement of the plots, which are the basic units of each field trial. Plots on which the same treatment was applied should be wide apart in the field, otherwise local factors, such as soil fertility or exposure to sunshine, could be mistaken for real efficacy compromising the reliability of the experiment (Johnston, 1849, p. 39).[13]

RES, the research programme of which was mainly focused on the growth of crops, had also to face the challenges posed by the rising discipline of genetics. Up until the 1930s it had yet to be decided "whether work of a genetical nature was in order or *ultra vires*" at Rothamsted and this disregard of genetical questions had consequences also on the field experiments, as the necessity to use the same crop variety throughout time was not immediately perceived.[14]

For instance, in the Broadbalk wheat experiment – the most famous among the Rothamsted long-term experiments which continues to this day – eight different wheat varieties were used from 1852 to 1918. Some

[11] Arthur Young's experiments on wheat are described in chapter 1 section 3 of his monumental course of experimental agriculture (Young, 1770). In agricultural science each comparative field experiment includes a certain number of units called plots – adjoining pieces of land of same size and shape clearly marked out in the field – each one receiving a different treatment, for instance a fertilizer, or combination of treatments. The results of the treatment(s) efficacy are then assessed confronting the yields of the different plots.

[12] The role of chemical research in promoting precision within agricultural science is discussed in Swijtink, 1994, pp. 1365–1366. An outline of the development of experiments in agricultural science from the seventeenth to the nineteenth century is in Fussell, 1935. Fussell argued that "[a] trial is not an experiment though an experiment is a trial" (Fussell, 1976, p. 47), but in the annual reports of RES trial and experiment are used almost as synonyms. I therefore followed the usage of my primary sources and considered the two words as interchangeable.

[13] Johnston's work is regarded as a start in the modern techniques of field experimentation (see Fussell, 1935, pp. 87–88).

[14] Report of the Meeting of the Sub-committee on animal husbandry, 2nd February 1932, Rothamsted Research Library and Archive (hereafter cited as RRes), FX 1.2. 1928–1933.

of these varieties were employed for just one year, others for decades, but in the late 1920s the plant breeder Rowland Biffen advised the Rothamsted director John Russell against a new change of variety because "[o]ne does not know how much one is monkeying up the results by using different wheats."[15] This was an intrinsic weakness for an experiment whose value relied in the repetition of the same scheme and whose results, recorded over a long series of years, were meant as a resource against the high variability of the elements under investigation.

The necessity to collect the results of the long-term field experiments, as the one in the Broadbalk field, prompted the creation of a data archive at Rothamsted. Besides the crops data, the archive hosted also meteorological records of rainfall, atmospheric pressure, and temperature collected at the station since the nineteenth century. Alongside the data archive a sample archive was created for the samples of soils, crops, manures and fertilizers collected in the field experiments.[16] RES was not alone in its decision to set up an archive. Recording and archiving had featured prominently in experimental farms and agricultural stations since the nineteenth century, and the historical records produced by agricultural institutions became exceptionally valuable.[17]

In the present account the data archive acted as a crucial element in the emergence of statistics at Rothamsted. The re-analysis of the long-term series of crops and meteorological data was, in fact, the first task given to Fisher to test whether statistics could be applied to the results of the Rothamsted experiments (Russell, 1966, p. 326). Moreover, during the 1920s and 1930s the long-term series of data offered suitable material for testing the analysis of variance by Fisher and his coworkers. On the other hand the traditional arrangements for the collection of experimental results and the physical location of the Rothamsted record archive were challenged by the new needs of an agricultural experimentation that heavily relied on statistical methods. Before addressing these topics, it is necessary to provide at first a general overview of the emergence of statistics in agricultural science at the turn of the twentieth century.

[15] Letter from R. Biffen to E. J Russell, 4th October 1929 (E. J. Russell Papers, RRes, RUS 2.7).

[16] For the history of the sample and data archive see Rothamsted Research, 2006.

[17] On the relevance of the fertilizer data accumulated at Rothamsted see Brassley, 1995, p. 468, and Rothamsted Research, 2006. For the value of recording and archiving see Johnston, 1849, p. 7.

Statistics in Agricultural Science

The first systematic interest for the statistical analysis of the experimental results arising in ‘‘some chemical, many biological and most agricultural and large scale experiments’’ in which ‘‘it is sometimes necessary to judge of the certainty of the results from a very small sample, which itself affords the only indication of the variability’’ (Student, 1908, p. 2) can be traced back to the chemist William Sealy Gosset. Gosset was a brewer for Arthur Guinness, Sons & Co. in Dublin. He is today mainly remembered for his statistical distribution, named *t* or Student's distribution, which is still in use for statistical analysis when the data available are very limited in number, i.e. they constitute a small sample.[18]

Gosset was influential in the application of statistics to the planning and analysis of agricultural experiments in Britain during the first three decades of the twentieth century. Due to Guinness' experimental work on barley breeding both in Ireland and Britain, he had the opportunity to gain a first-hand experience of field trials and to make contacts with the two main centres for British agricultural science in the early 1910s, RES and Cambridge University. Since 1910 Gosset was in correspondence with the Rothamsted director, Hall, about the use of statistical methods for the examination of field trials.[19] During the 1910s he began his life-long scientific correspondence with Ronald Fisher – Gosset might even have facilitated Fisher's appointment at RES – and during the 1920s he was the principal discussant of Fisher's statistical ideas on the planning and analysis of field experiments.[20]

In the early 1910s more contributions on the use of statistics in agricultural experiments were published in Britain. The two that had the greater impact were authored respectively by Thomas B. Wood, Cambridge professor of agriculture, and by his friend and colleague, the

[18] Student's distribution and its related tables of the probability integral were the first statistical tools that addressed explicitly the analysis of small samples of experimental data. On Gosset see Pearson, 1939, 1990. On Gosset's statistical efforts for Guinness see also Mackenzie, 1981, pp. 111–116.

[19] On A. D. Hall's interest for the use of statistics in field experiments see also Hall, 1909, 1931.

[20] Gosset's acquaintance with Beaven is mentioned in Pearson, 1939, p. 230. For Gosset's scientific collaboration with A. D. Hall see the letter from W. S. Gosset to A. D. Hall, 8th December 1910, RRes, STATS 12. A published version of W. S. Gosset and R. A. Fisher scientific correspondence (1915–1936) is Gosset, 1962. On Fisher's appointment at Rothamsted see in particular Gosset, 1962, Letter No. 3, 30th December 1918, and Mackenzie, 1981, p. 211.

astronomer Frederick J. M. Stratton, and by the already mentioned Rothamsted director, Hall, and by the agriculturist W. B. Mercer (Wood and Stratton, 1910; Mercer and Hall, 1911). These publications appeared in 1910 and 1911 in the *Journal of Agricultural Science*, the same venue where Fisher's papers on analysis of variance would be published a decade later.

These papers offered to the readers a discussion of error theory applied to data gathered in agricultural experiments. At the beginning of the twentieth century, in fact, the application of statistical methods to agricultural research involved mainly the method of least squares borrowed from astronomy.[21] However, the small samples, not rarely biased by systematic errors, involved in agricultural research were not really suitable for applying the astronomical methods of data analysis (Swijtink, 1994, pp. 1366–1367). New statistical tools, such as the ones developed at first by Gosset and later by Ronald Fisher, were required to deal with the sparse experimental results available in agricultural research.

Gosset's work and the papers here mentioned are not the only forerunners of Fisher's contributions to the planning and analysis of field experiments in agriculture. At the end of the nineteenth century probability and statistics were already being employed in agricultural experiments in Germany and German speaking countries, where agricultural research had considerably grown during the century due to the influence of the chemist Justus von Liebig and the establishment of several experimental farms (Gigerenzer et al., 1989, p. 85; Swijtink, 1994, pp. 1365–1367). Even the authors that in the 1920s and 1930s presented analysis of variance and experimental design to their fellow researchers in agricultural science pointed out to their readers a richer tradition of statistical methods applied to agricultural research, albeit in the form of simple mean deviations or astronomical methods, such as least squares.[22]

In addition, it is important to mention that in 1912 the Cambridge School of Agriculture hired the statistician George Udny Yule to advise the local agronomists and breeders, and subsequently in the 1920s another relevant contributor to twentieth century statistics, Jerzy

[21] The method of least squares is a method of fitting experimental data to a curve minimizing the squares of the errors. It was introduced at the beginning of the nineteenth century by the French mathematician A. M. Legendre and represented the *leitmotif* of mathematical statistics in the nineteenth century (Stigler, 1986, pp. 11–61).

[22] See, for instance, Eden, 1935, p. 132.

Neyman, began his career in agricultural research analysing experiments at the Agricultural Research Institute in Bydgoszcz, Poland.[23]

It is thus evident that in the early decades of the twentieth century the interest for integrating statistics into agricultural experimentation was a general trend and not a British specificity, let alone a peculiar feature of RES. The successes achieved there by analysis of variance and experimental design has made the Rothamsted case notable, but since the nineteenth century empirical solutions and attempts to theorize best practices to minimize errors in the outline of field experiments and in the analysis of their results had been developed. This tradition culminated in the 1910s and 1920s with the appointment of statisticians, like Yule, Fisher and Neyman, into agricultural research institutes.

The Opening of the Rothamsted Statistics Department

Ronald Fisher arrived at Rothamsted with a temporary position in October 1919, called by the then Rothamsted director, John Russell. When Fisher arrived at the agricultural station he had a degree in mathematics from Cambridge University, maintained an active association with the British eugenics movement which had sponsored his early research career in genetics, had worked briefly as a statistician in the City of London and, since 1915, had gained appointments as a mathematical schoolmaster (Fisher Box, 1978, Chaps. 1–4).

Russell's accounts of Fisher's arrival at Rothamsted emphasize the role that the series of data collected at the station had for the appointment of a statistician. According to these accounts, in fact, Fisher was hired to extract more information from the results of the field experiments and the records of the meteorological observations held at the station (Russell, 1935, 1956, pp. 131–132; 1966, pp. 325–326).[24] However, by 1919 the director of RES must have been aware that a statistician, besides dealing with the past data, could offer

[23] On Udny Yule's work in Cambridge see Charnley, 2011, p. 63. On Neyman, Reid, 1998, pp. 43–44.

[24] All Russell's accounts are reconstructions *ex post* of Fisher's career at Rothamsted. The first one was written at Fisher's resignation in the 1930s, while Russell's autobiography and his history of British agriculture were written decades later. Despite the consistent time lapse between the first account and the other two, they are all suspiciously alike, as if the version of Fisher's appointment given in the 1930s had become canonical.

an immediate contribution to the experimental research of the station.[25] The statistician's mission, therefore, is likely to have been, since the beginning, both a re-evaluation of the past data and an active engagement in the program of experimental research at the institution. Ronald Fisher's analysis of variance fulfilled such dual mission being a flexible instrument for data analysis, applicable to historical series of data and to the results of the current experiments as well.

Ronald Fisher's appointment at Rothamsted became permanent in 1920, when he was granted a department of his own. During the period he spent at Rothamsted Fisher could count on one or (at most) two assistant statisticians (Table 1 in Appendix) and a handful of human computers (Table 2 in Appendix). The assistant statisticians contributed to the examination of the historical series of experimental and meteorological data collected at Rothamsted and at the associated farm of Woburn, took part in the planning and analysis of the station field trials, participated in the study of meteorological factors in agriculture, and in the preparation of the Rothamsted annual reports, especially with reference to the results of the field experiments.

Alongside the staff employed by the experimental station, during the time that Fisher spent at Rothamsted, over fifty people came to his department as visiting (or voluntary) workers (Table 3 in Appendix) to learn analysis of variance and experimental design. They were supported by research institutions, private companies or through scholarships offered by foundations and research councils. The visiting workers contributed to the analysis of the Rothamsted data, consulted Fisher in the solution of their own problems, and promoted the dissemination of Fisher's statistical methods in their disciplines – agronomy, botany, plant breeding, statistics, sociology to name a few – contributing to the prompt success of analysis of variance and experimental design in research.[26]

Besides statistical work, the tasks undertaken by Ronald Fisher and his co-workers at Rothamsted involved data management and com-

[25] In the spring of 1923 Fisher had already completed the examination of a current Rothamsted experiment using the analysis of variance (Fisher and Mackenzie, 1923).

[26] On the voluntary workers at Rothamsted see Fisher Box, 1978, pp. 241–243. N. S. Hall has argued that the voluntary workers contributed to the dissemination of Fisher's statistical methods in their own disciplines and institutions (N. S. Hall, "Did Fisher's voluntary workers at Rothamsted make a difference in the spread of statistical techniques in agriculture?," unpublished talk). However, this general trend admits exceptions. A counterexample is discussed by the historian Joel Hagen and relates to the botanist Edgar Anderson, who came to Fisher's department in 1929, but did not employ afterwards Fisher's methods (Hagen, 2003, p. 361).

puting. The statistics department actively contributed to the surveillance and safeguarding of the Rothamsted records, which were "transferred to the Statistical Dept. with a view to their being eventually incorporated with the records in that department" in 1927.[27] Fisher took them under his responsibility and by the mid-1930s the statistics department hosted records of the field experiments, further materials deposited by other departments for statistical analysis, and some historical records of the station.[28]

The physical move of the station records under Fisher's surveillance contributed to setting the statistics department at the core of the scientific life of the agricultural institution, consolidating the role that statisticians gained with their involvement in the planning and analysis of experiments. Since Fisher's time, the statistics department and its followers have been a key stakeholder in the management of station data.[29]

Besides data management, the development of analysis of variance and experimental design imposed a qualitative shift in terms of equipment and labour organization for computing, as already hinted by the existence of a staff of human computers. The human computers in the Rothamsted statistics department were mainly women, without university education, earning a modest salary, and subordinated to the scientific staff that organized and supervised their work.[30]

Before the creation of Fisher's department it is likely that the experimental station did not possess any calculating machine and in the 1930s some departments of the station still borrowed or rented calculators from other departments.[31] On Fisher's appointment in 1919 a calculating machine was rented for him and in 1921 or 1922 he acquired a Millionaire motor calculator of his own.

In the 1920s the Millionaire was an expensive instrument, because it was one of the few calculators able to multiply directly on the basis of a

[27] RRes, STA 2.1, 11th July 1927.

[28] Interim report (1935) on the system of recording results at Rothamsted, Woburn and on the Farm, RRes, RUS 4.31.

[29] The Rothamsted statistics department – later renamed biomathematics and bioinformatics department, now department of computational and systems biology – has contributed throughout the decades to the conservation of the station records maintaining its own autonomous archive.

[30] On the history of human computers see Grier, 2007. In particular on the involvement of human computers in agricultural statistics see Grier, 2007, pp. 159–169.

[31] RRes, STA 2.1, 11th January 1934. In the Rothamsted accounting book from 1913 to September 1919 no calculating machine is mentioned (RRes, LAT 34, Rothamsted Laboratory Cash Account 1913–30th September 1919).

multiplication table, a much speedier process than the repeated addition performed by most machines. It was therefore well suited for the calculation of the several sums of squares required in the application of the analysis of variance. Fisher's model was motor-driven and thus avoided to its user the physical strain involved by operating a hand-cranked machine.

Fisher developed a deep affection for the Millionaire and passed on his affection for this type of calculator also to Frank Yates, at first his assistant and then his successor at Rothamsted. The Millionaire calculator credited as being Fisher's own was still in Yates' office at Rothamsted in the 1970s.[32]

The Millionaire was probably the only calculating machine initially available to the Rothamsted statisticians, but in 1925 Fisher's department began to acquire more equipment on a regular basis.[33] In the Rothamsted statistics department there were also computing tools such as slide rules and mathematical tables, which, to some extent, compensated for the scarcity of the calculating machines that were never in large supply.[34]

In the first half of the 1920s the Rothamsted statistics department acquired two cylindrical slide rules for the moderate cost of a few pounds. In 1922 it also subscribed to the journal *Biometrika*, a source of relevant mathematical tables useful for statistics, and purchased some of the booklets in the series *Tracts for Computers*, whose tables were considered a working tool for every human computer of the time.[35]

Slide rules and mathematical tables were computing instruments easy to use and of limited cost. The former were analogue devices for mechanical calculation, especially multiplication and division, usually shaped as standard rulers or cylinders and printed with one or more logarithmic scales. They required only a basic grasp of logarithms and computations could be done easily moving the sliding part of the device – whence the name – along the selected scale.

[32] For Fisher's Millionaire at Rothamsted see Gosset, 1962, Letter 15th October 1924; Fisher Box, 1978, pp. 273–274; Ross, 2012. For the technical features of the Millionaire see Martin, 1992, pp. 119–125. In Fisher's biography (Fisher Box, 1978), Frank Yates is portrayed operating the Millionaire (Plate 23).

[33] For the acquisition of calculating machines in Fisher's department see RRes: LAT 34, December 10th 1919, 27th April 1926; STA 2.1, 6th January 1925 and 6th December 1929.

[34] Letter from R. A. Fisher to F. Yates, 5th December 1931, RRes, STATS 7.11.

[35] For the purchase of slide rules and mathematical tables in the Rothamsted statistics department see RRes LAT 34, 11th April 1922, 28th August 1922, 8th February 1924; RRes STA 2.1, 4th November 1921, 8th December 1921, 7th May 1926.

Mathematical tables provided, instead, the reader with tabulations of relevant values for standard functions, avoiding the necessity of doing complex or tedious calculations from scratch. Interpolation formulas were used to extract from the figures tabulated the values in which the reader was interested.[36]

Despite the availability of new computing equipment the examination of the agricultural experiments remained a demanding task for both the statisticians and the human computers of the department. Since the season 1925–1926 the summary tables of the replicated experiments in the Rothamsted reports began to be supplied with the standard error calculated using the analysis of variance (RES, 1927, p. 122). The analysis of the agricultural experiments was done by hand and on desk calculators, a procedure that remained almost unchanged until the application of electronic computers to agricultural research in the 1950s (Yates, 1960, p. 210). The time employed by the team of human computers varied in relation to the complexity of the experimental set up. The most complex designs required several weeks and even months to be completed. The heavy computational labour was worsened by the seasonality of agricultural experiments and thus by the accumulation of the experimental results in the same period of the year.

The computing activity in the Rothamsted statistics department was not limited to the analysis of agricultural experiments. During his years at Rothamsted, Fisher was actively engaged in the British Association Mathematical Tables Committee, in which were co-opted also his assistants, John Wishart and Oscar Irwin, and the Committee made available for the Rothamsted statisticians a Brunsviga calculator.[37]

Notably, Fisher's efforts as table maker were focused on the preparation of computing tools, which could be employed in the application of his own statistical methods. The tables in *Statistical Methods for Research Workers* (1925), Fisher's textbook on analysis of variance and

[36] For an overview of the slide rules available in Britain at the beginning of the twentieth century see Horsburgh, 1914, pp. 155–180. A source of information on the long and complex history of mathematical tables is Campbell-Kelly et al., 2003.

[37] On the history of the British Association Mathematical Tables Committee and its association with the Rothamsted statistics department see Croarken, 2003. Brunsviga calculating machines performed computations using a mechanism based on wheels with a variable number of teeth. The input of figures in the machine and the display of the result, both depended on setting of levers and turning of cranks that put in motion the pinwheels. They were very popular at the beginning of the twentieth century and appreciated for scientific computation, but unlike the Millionaire, Brunsvigas performed multiplication as repeated addition and were, therefore, slower. On the technical features of Brunsviga calculating machines see Martin, 1992, pp. 109–113.

(in part) experimental design, were prepared by Fisher with the help of his first assistant Winifred Mackenzie (Fisher, 1925). The tables were computed in accordance with the suggestions on statistical significance presented in the book, making the application of Fisher's methods straightforward and linking statistics to computing for the users of analysis of variance and experimental design.[38]

Fisher's textbooks *Statistical Methods for Research Workers* and *The Design of Experiments*, published ten years later, became a necessary companion for many experimental scientists and statisticians and Fisher came to be a best-selling author (Fisher, 1925, 1946, 1947).[39] However, the technical presentation of analysis of variance and experimental design conveyed by these books is not enough to understand the genesis of these statistical methods. Their origins must be complemented by an examination of how analysis of variance and experimental design were intertwined with the research done at Rothamsted. Therefore, the following section will sketch both the main technical features of Fisher's methods and the collaboration between statisticians and experimenters that made their development possible.

Analysis of Variance and Experimental Design

Ronald Fisher described the analysis of variance as "a simple method of arranging arithmetical facts so as to isolate and display the essential

[38] In *Statistical Methods for Research Workers* Fisher suggested a 5% threshold for statistical significance (Fisher, 1925, p. 79). The tables in the book appendix were, in consequence, computed for fixed values of probability. The column with $p = 0.05$, corresponding to the 5% threshold, was therefore immediately accessible to the users of Fisher's book. For the conventional meaning of the 5% threshold and the popularity it gained in experimental research see Porter, 1996, pp. 211–212; Gigerenzer et al., 1989, p. 78. The efforts of Fisher as table maker interested in the promotion of his statistical methods were corroborated in the 1930s by a comprehensive collection of statistical tables for the application of analysis of variance and experimental design (Fisher and Yates, 1938).

[39] The success of Fisher's books is a good yardstick of the popularity acquired by his statistical methods. By 1963, 36,000 copies of the English edition of *Statistical Methods* had been sold and the book had been translated into French, German, Italian, Spanish and Japanese; instead *The Design of Experiments* sold 32,500 and was translated into Italian and Spanish (Letter from Oliver and Boyd to F. Yates, 10th June 1963, Oliver and Boyd Collection, Acc.5000/Roneo System/Box 980, National Library of Scotland).

features of a body of data with the utmost simplicity."[40] The rationale behind the analysis of variance, in fact, is to split the global variation of a phenomenon, i.e. the variance, in additive components, each one linked to an independent cause of variability. In an experiment on the efficacy of fertilizers, with the analysis of variance it is possible to examine the variation of the yield both within plots that receive the same fertilizer or combination of fertilizers and between sets of plots that receive a different treatment. The global variation of the yield in the plots is subdivided into several components and it is possible to measure the effects of distinct causes on the final result. For the Rothamsted field trials this meant that factors, such as the unequal fertility of the soil, could be set aside from the efficacy of fertilizers, which was the real point of interest.

The analysis of variance offered an alternative approach to the method of correlation that had dominated British statistics to that date. In biometry correlation was made popular by the statistician Karl Pearson, who worked at University College London at the turn of the twentieth century.[41] Pearson developed a coefficient able to measure whether two variables varied together (Pearson's correlation coefficient) and nowadays the statistician's name is mainly associated to this coefficient (Porter, 2006, p. 1).

However, in experimentation correlation could give only partial answers. In the preliminary stages of research it was helpful to know whether two quantities were associated or not, but, as remarked by Ronald Fisher, a correlation coefficient was seldom the form in which the final results of any controlled experiment were presented (Fisher, 1946, p. 175). Moreover, Pearson's coefficient had several limitations. In particular, it described only linear relations between variables and was sensitive to outliers.

The analysis of variance, instead, offered a tabular arrangement for displaying the experimental results. The data were subdivided in classes (or groups) according to their cause of variation making clear the structure of the experiment, as described below in a specific case. Fur-

[40] Letter from R. A. Fisher to G. W. Snedecor, 6th January 1934, G. W. Snedecor Papers, Special Collections Department, Iowa State University Library, RS 13/24/51, Box 1, Folder 9.

[41] Karl Pearson and Ronald Fisher were lifelong enemies, yet Fisher could not disregard Pearson's role in British statistics. Both the journal *Biometrika* and the series *Tracts for Computers*, mentioned above, were edited by Pearson and the analysis of variance was introduced in *Statistical Methods for Research Workers* using the concept of intraclass correlation (Yates, 1951, pp. 23–24). On Pearson see Porter, 2006; in particular on correlation, pp. 257–261.

thermore, unlike the method of correlation, the analysis of variance did not provide only instruments to estimate the association between variables, but offered also tools to evaluate the significance of such association.

The tests of significance provided by the analysis of variance were more flexible than the test derived from Student's distribution. Student's test, in fact, could be applied with confidence only when the means of just two experimental samples were compared. A repeated application of the test to more than two samples, taking the means two at a time, increased, instead, the risk to find spurious significance, or, on the contrary, to overlook it (Hagen, 2003, p. 368).

On the other hand, the analysis of variance was designed with the complexity of agricultural and biological experiments in mind, and could confront several experimental treatments at a time. It overcame the limitations of Student's test not comparing directly the means of the classes of experimental data, but working on their variance.

Due to the additive property of the variance, it was possible to separate the component of the variance ascribed to the random error from the components of the variance that measured a real difference between the means of the different classes of experimental data. These latter components of the variance could then be tested using the F test, named in honour of Ronald Fisher, concluding whether the variation between the means of all the classes, or any subset of them, was significant or not. Since the 1920s and 1930s tests of significance became popular among experimental scientists and began to be routinely employed to assess whether a set of experimental results satisfied a certain hypothesis or not (Yates, 1951, p. 32).[42]

While the engagement with experimental research helped to shape the structure of the analysis of variance, the word variance and the idea to split the global variation into additive components predated Fisher's appointment at Rothamsted. Fisher used the term variance for the first time in 1918 in the seminal paper in which he proved that Mendelism and biometry were compatible (Fisher, 1918). Donald Mackenzie and Theodore Porter have claimed that the analysis of variance was fully developed in Fisher's 1918 paper and that it derived from Fisher's involvement in eugenics (Mackenzie, 1981, p. 211; Porter, 1986, p. 316).

However, primary and secondary sources offer more convincing evidence that the development of analysis of variance took place during

[42] Not rarely experimental scientists and their statistical consultants have placed too much emphasis on tests of significance alone, rather than conceive them as just one component of the process of data analysis (Yates, 1951, pp. 32–33).

Table III.

Variation due to	Degrees of freedom	Sum of squares	Mean square	Standard deviation
Manuring	5	6,158	1231·6	35·09
Variety	11	2,843	258·5	16·07
Deviations from summation formula	55	981	17·84	4·22
Variation between parallel plots ...	141	1,758	12·47	3·53
Total	212	11,740	—	—

Figure 1. "In Table III is shown the analysis of the variation [...]; the mean square deviation is found by dividing the sum of squares in each class by the number of degrees of freedom [degrees of freedom for manuring and variety are computed subtracting 1 to the total number of variables], while the standard deviation is shown in the last column. When this value is significantly greater than the standard deviation of the differences between parallel plots, we may conclude that the corresponding effect is not due to chance" (Fisher and Mackenzie, 1923, p. 316). The table was originally published in Fisher and Mackenzie, 1923, p. 316. Reprinted with permission of Cambridge University Press

Fisher's work at Rothamsted. According to the station reports, "[t]he first example of an analysis of variance in its modern form was the examination of the results of T. Eden's experiment in 1922 on the response of different potato varieties to manures" (RES, 1927, p. 28).[43] Fisher and his statistical assistant Winifred Mackenzie examined Eden's field trial and presented their statistical results in tabular form (Figure 1).

In Eden's experiment the field was split in two sections, one with and the other without farmyard manure. Each section was then further divided into thirty-six small plots, where twelve potato varieties were planted each one three times in a chessboard arrangement. In each plot there were three rows of seven plants of potatoes each: one row received only basal manuring, one row basal manuring and sulphate of potash, one row basal manuring and muriate of potash. In all, therefore, six manurial treatments were tested (dung/undunged series; basal row/chloride row/sulphate row).[44]

The structure of the table allowed experimenters to identify immediately the four main sources of variation in the field trial, that is the variation due to the twelve potato varieties, the variation due to the six manurial treatments applied, the differences between the potato

[43] The paper mentioned in the report is Fisher and Mackenzie, 1923.

[44] There were some deviations in the actual implementation of the experiment from the theoretical plan here described, because a few of the potato plots were destroyed.

varieties in response to their manurial treatment (deviations from summation formula) and the variation between parallel plots in the field.[45] The tabular arrangement became a hallmark of the analysis of variance. As explained for the potato experiment, in fact, it was effective in revealing at a glance the structure of the experiment and its relevant results and facilitated the tests of significance on the data (Fisher, 1947, p. 50).

The analysis of variance featured prominently in the papers of the series ‘‘Studies in crop variation,’’ published by Fisher and his Rothamsted co-workers from 1921 to 1930 in the *Journal of Agricultural Science*. The *Journal of Agricultural Science* was a publication addressed to researchers engaged in agricultural science rather than biologists or eugenicists and Fisher's choice suggests again that agricultural research was the primary experimental context to which the analysis of variance aimed in the 1920s.[46]

The historian Joel Hagen also sets the development of analysis of variance in the context of Fisher's work in agricultural statistics at Rothamsted, as does John Aldrich, who points out that in the 1918 paper on Mendelian inheritance there is no statistical inference (Hagen, 2003, p. 368; John Aldrich personal communication). Aldrich has also provided a comprehensive reconstruction of the earliest uses of the word ‘analysis of variance’ from which a chronology in the development of Fisher's statistical method can be outlined (Aldrich, 2007).[47] The analysis of variance arranged in tabular form first appeared in July 1923 – in the above mentioned paper on the potato experiment –, and in the December of the same year in a note written by Fisher for a paper, again on agricultural matters, published by Gosset (Fisher and Mackenzie, 1923, p. 316, Table III; Student, 1923, p. 283, footnote).

Porter has also claimed that while the analysis of variance was the result of Fisher's involvement in eugenics, experimental design was linked to his engagement with the research at Rothamsted (Porter, 1986, pp. 317–318). But Porter's claim clashes with Fisher's approach to agricultural science. For Fisher planning and analysis were never independent because only a suitable experimental design allows for an

[45] Fisher's 1923 statistical examination of this experiment, however, was not flawless as pointed out by Fisher Box, 1978, p. 162, and Cochran, 1980, pp. 17–20.

[46] The data that prompted these studies were taken from the Rothamsted experiments, both the annual trials and the long-term experiments.

[47] John Aldrich mentions the first paper of the series on crop variation as the first publication in which the technique known as analysis of variance was explicitly addressed (Aldrich, 2007). In this paper, however, there is no table, the customary form in which Fisher arranged the analysis of variance.

examination of the results with the analysis of variance.[48] According to Fisher, in fact, ‘‘the estimate of error is not created by the statistician out of nothing, but is inferred from the observations by a process of estimation analogous to that used in the estimation of any other quantity, and requiring the same care in experimental design if the estimate is to be a valid one’’ (Fisher, 1934, p. 47).

At Rothamsted Ronald Fisher singled out four basic principles in arranging field trials: replication of experiments on small plots of land; randomisation, i.e. the chance allocation of treatments to plots; use of factorial experiments in which several questions are combined together; ‘confounding’ that is the decision in relevant cases to sacrifice information on minor interactions (Fisher, 1934, pp. 46–49).[49]

Randomisation is nowadays recognised as Fisher’s primary breakthrough in experimental design (Hall 2002, 2007; Gigerenzer et al., 1989, pp. 74–76, 85–87). It was a necessary pre-condition for examining the experimental results with the analysis of variance. Randomisation was a tool used to limit the variability of the soil or, in an experiment where multiple factors were tested, to guard against the possibility that the mutual influences of these factors might be mistaken for the treatment’s efficacy. In agricultural experiments randomisation was achieved through two basic schemes, the Latin square and randomised blocks (RES, 1927, pp. 28–29).[50]

As previously remarked, the development of analysis of variance and experimental design cannot be reduced to their technical aspects. In his work at Rothamsted Fisher relied on the collaboration of the Rothamsted researchers who helped him to test his statistical ideas in the fields of the station. The annual reports of RES describe, in fact, analysis of variance and experimental design as ‘‘the outcome of long previous investigations in which several workers, including the agriculturist, the ecologist, the plant physiologist and the statistician took

[48] ‘‘Experimental design and the analysis of experimental data are intimately connected […] and Fisher made it a cornerstone of his theory of experimental design’’ (Swijtink, 1994, p. 1368).

[49] During his years at Rothamsted Fisher wrote three more contributions on the arrangements and statistical analysis of field experiments (Fisher, 1926, 1931; Fisher and Wishart, 1930).

[50] In a Latin square the plots are arranged with as many rows and columns as the number of treatments to be tested, while in a randomised block the experimental area is divided into strips or blocks, each one containing one plot of each treatment. In both cases treatments are assigned to the plots at random.

part" (RES, 1927, p. 27).[51] The ecologist Thomas Eden, in charge of the field experiments at Rothamsted from 1923 to 1927, and the plant physiologist Ernest Maskell, member of the station staff from 1924 to 1926, were the field workers who closely collaborated with Fisher in the practical implementation of analysis of variance and experimental design.[52]

Eden, trained in chemistry at the Victoria University of Manchester, and Maskell, educated in botany at Cambridge, were in charge of the field observations, contributed to set up the uniformity trials for determining the experimental error of the field trials, tested Latin squares and randomised blocks in the field, and collaborated in the development of sampling techniques for the crop harvest.[53]

Both Eden and Maskell adopted analysis of variance and experimental design in their research. Eden added on his résumé that 'statistical control' was a feature of his work on soils and crops since his time at Rothamsted. Maskell as well "rapidly acquired a sound basis of statistical knowledge" and statistics contributed to his further research activity at the Cotton Research Station in Trinidad (Briggs et al., 1961, p. 162). Eden and Maskell contributed also to the dissemination of Fisher's statistical methods among their fellow researchers publishing simplified accounts, which explained the application of analysis of variance and experimental design to agricultural trials (Maskell, 1929; Eden, 1935).

It is thus evident that Fisher's statistical methods were not conceived merely at the statistician's desk, but through interaction with the Rothamsted experimental scientists. For this reason, as it is argued in the following section, analysis of variance and experimental design rapidly gained institutional space at the station and were successfully integrated into its research programme.

The Role of Statistics in the Rothamsted Research Programme

In 1924 a Field Plots Committee was created at RES "to make sure that experiments are statistically and agriculturally sound, that they are sited

[51] See also the Ministry of Agriculture and Fisheries, Agricultural Research Council, annual report 1924–1925, the National Archives of the UK, DSIR/36/4239.

[52] Biographical information on T. Eden and E. J. Maskell can be found, respectively, in Thomas Eden's résumé, ca. 1946, E. J. Russell Correspondence, Museum of English Rural Life, University of Reading, FR HERT 11/1/1; Briggs et al., 1961.

[53] For the contributions given by Eden and Maskell to the development of analysis of variance and experimental design see RRes, FX1.1.1, 31st January 1924; RES, 1925, pp. 14–15, 39–40; 1927, pp. 26–29; 1929, p. 39.

on suitable land and that both farm staff and experimenters know their respective responsibilities at every stage'' (Garner, 1962, p. 180).[54] In the 1920s members of the Field Plots Committee included the director Russell, the staff concerned with the field experiments – initially the crop ecologist Eden, who was the first secretary of the Committee, and the plant physiologist Maskell – the farm manager, Fisher, and his assistant statisticians.

From 1925 the Committee considered the suggestion to re-examine the design of all the field experiments at the station ''in the light of Mr Fisher's methods'' and a year later it was decided that ''proposals for field experimental designs might be made known to the Secretary for consultations with Dr Fisher before coming before the meeting.''[55] Since the second half of the 1920s, the overall plan of the Rothamsted field experiments from year to year was discussed using exclusively Latin squares and randomised blocks and only the long-term experiments were maintained in their original format.[56]

Besides their advisory role, Fisher and his assistants contributed to shaping the experimental plans of the institution indicating whether a trial was worth continuing or not, giving suggestions in order to combine several investigations into the same experiment, and actively proposing experiments.[57] Fisher's assistants – at first John Wishart and later Frank Yates – were also in charge of giving full reports of the statistical analysis of the annual experiments before the Committee and this reinforced their first-hand relation with the experimental program of the institution.[58] Since the late 1920s the Rothamsted statistics department cooperated also with the plant physiology department in the development of sampling techniques for harvesting crops and for the study of their progress and growth in the field.[59]

[54] The activity of the Field Plots Committee, its members, the problems it discussed and the role that statisticians had in it can be reconstructed from the minutes of its meetings. RRes has a complete record of the Field Plots Committee Minutes (FX 1).

[55] RRes, FX 1.1.1, 26th October 1925; RRes, FX 1.1.1, 26th November 1926.

[56] In each year the Field Plots Committee examined the experiments for the following season discussing plans and arrangements. A few examples of these discussions are RRes, FX 1.1.1, 13th November 1928 and 27th May 1931.

[57] RRes, FX 1.1.1: 26th November 1926, 7th March 1927, 28th September 1927, 4th October 1929, 1st February 1932, 22nd February 1927, 13th November 1928, 21st June 1929, 4th October 1929, 2nd December 1930, 12th January 1931, 4th December 1931.

[58] RRes, FX 1.1.1: 22nd January 1929, 4th December 1931.

[59] The technique for the random sampling of the yield is described in RES, 1929, p. 39. Further details are in R. A. Fisher's contribution (p. 615) to a discussion before the Royal Statistical Society (Neyman, 1934).

The application of statistics was not limited to field experiments as Fisher's methods were also suitable for the laboratory research carried on at Rothamsted. Analysis of variance and experimental design, in fact, were adopted in the bacteriology department for the study of the numbers of bacteria in soil, in the entomology department for studying bees and other insects, in the chemistry department for extracting information from the figures accumulated during laboratory investigations (RES, 1931, p. 53). Experimental design was introduced as well in the practice of laboratory research. Already in the early 1930s Frank Yates advised the botanist Winifred Brenchley to randomise her pot cultures for testing the effects of boron dressing on beans, otherwise, competition for light and air among the plants within each set of replicates would have concealed the real effects of the fertilizer (Yates, 1990, p. xxii).

The prompt passage of analysis of variance and experimental design from field trials to laboratory investigations is evident in *Statistical Methods for Research Workers* and *The Design of Experiments*. Both books addressed the application of statistics in experimental research through practical examples taken from field and laboratory research in agricultural science and biology summarising Ronald Fisher's experience as a consultant to all the Rothamsted experimental scientists.

Rethinking Agricultural Research in Statistical Terms

Fisher's statistical methods increased the overall complexity of the Rothamsted field experiments and required new instruments for their implementation. In order to assist the farm staff, the secretary of the Field Plots Committee revised the experimental plans for the year with the field superintendent (Weston, 1962, pp. 32–33). The field superintendent was also in charge of preparing and storing the farm records which consisted of 'white books' – for recording copies of the experimental plans, instructions for the realization of the experiments, dates and details of the field work and crop observations – and a 'harvest book' with the weights of the crop yields, which was handed to the statistics department for the preparation of the station report.[60]

[60] Interim report (1935) on the system of recording results at Rothamsted, Woburn and on the Farm, RRes, RUS 4.31. See also Weston, 1962, p. 48.

To comply with the requirements of Fisher's statistical methods new drills for sowing seeds and new strategies for manuring were tested in the field, because these two passages were critical for the reliability of the trial (RES, 1931, p. 48). For the harvest of the experimental plots of cereal crops a small thresher was purchased, and to reduce the dispersion of the yield from the field, where it was cut, to the farm, where it was threshed, the whole product from a plot was placed in a cloth and tied into a bundle. For harvesting root crops, instead, a portable scale was provided in order to do the weighing in the proximity of the experimental plots.[61]

Aside from the tools and practices adopted in the field, statistics impacted also on the data collection system established at Rothamsted since the nineteenth century. With Fisher's statistical methods further information should be archived due to the more complex experimental settings. The detailed plans of the field trials should be set out on paper, the field practices adopted in the trials were also recorded, as well as observations on the growth of crops that were deemed useful for the statistical analysis of the data.[62]

The new arrangements for field trials required also a new format for the presentation of the experimental results in the station reports and Ronald Fisher was instrumental in their redesign.[63] The experiments on crop and fertilizers were now presented indicating the detailed plan of the trial, the statistical analysis of the results, and the original data. The statistics department became thus a major stakeholder in the management of the Rothamsted experimental results.[64]

It is not surprising that the emergence of statistics at RES reshaped the collection of the results of field experiments and their presentation. As argued by Staffan Müller-Wille in relation to the plant breeding

[61] A description of the changes to the Rothamsted field practices in the 1920s is in Weston, 1962, pp. 17–37. The harvest of each experimental plot was very limited due to the small size of the plots (a choice made to minimize variations within the experimental area) and to the necessity of discarding the rows of the crop closer to the plot borders because they were disturbed by contour effects.

[62] The layout and working details of the field experiments, and the observations on plant physiology, were held by the field experiments department. Some of these data were also duplicated in the farm records. (Interim report (1935) on the system of recording results at Rothamsted, Woburn and on the Farm, RRes, RUS 4.31.) Further information on the data collected during the growth of crops is in RRes, FX 1.1.1, 31st January 1924.

[63] Res, FX 1.1.1, 2nd October 1925.

[64] See, for instance, the final section (pp. 121–155) on field experiments in RES, 1927.

station of Svalöf, in fact, record-keeping systems cannot be considered neutral tools, but constrain and are constrained by the scientific research pursued by the institution that adopts them (Müller-Wille, 2005). The practices for the management and dissemination of the Rothamsted data related to field trials had been formalised well before the emergence of statistics and their transformation during the 1920s is just a further proof that in ten years the Rothamsted statistics department had become a crossroad for all the field research conducted at the institution, from experimental design to the sampling of the crop at harvest, to the best methods of sowing or manuring, to the final analysis of the experimental results, and their public presentation and archiving.

Thus, since the second-half of the 1920s the Rothamsted statisticians were able to compete for attention and prestige with traditional departments of the station, such as the farm and the field experiments section. In fact, with the application of analysis of variance and experimental design to field trials, the Rothamsted experimental scientists, who formulated the scientific questions, became only one of the actors involved in the field trials, and had to acknowledge as essential to experimental research the mathematical and computing expertise of the statisticians who worked at their side.

The change was significant, but it was accepted because statistics could offer in exchange greater precision in experimental research, especially in relation to field trials. With the new statistical methods, in fact, the precision of the Rothamsted field experiments was between 2 and 4% (in 1929), while traditional experiments rarely gave an accuracy superior to 10% (RES, 1930, pp. 45–46). As a benchmark of the accuracy of the experiments the tables that summarised the results of the replicated field trials at Rothamsted began to report systematically the standard error computed with the analysis of variance (RES, 1927, p. 122).

The Rothamsted reports constantly emphasised the increase in precision as the improvement offered by Fisher's statistical methods resonated with the Rothamsted agenda to contribute to the development of better agricultural practices. Smaller experimental errors, in fact, were crucial in agricultural science because a variation of 5% in the gross yield could make all the difference between profit and loss for a farmer (RES, 1925, p. 38).

The higher precision, however, had its drawbacks. The field trials planned according to Fisher's principles of experimental design required a greater number of replicated plots and therefore were more costly than the traditional field experiments. These economic issues could not be disregarded, as experimental costs were a long-standing problem in agricultural science, even in a successful institution like Rothamsted, which could count on both private and public funding. At the experimental station the only solution in time was to restrict the programme of the annual experiments setting a limit to the number of plots that it was possible to cultivate each year.[65]

Conclusion

Field and laboratory are cultural domains "where different languages, customs, material and moral economies, and ways of life prevail" (Kohler, 2002, p. 5). Yet their demarcation is not clear-cut and they are separated by a border area where "laboratory and field practices can meet and mingle" (Kohler, 2002, p. 51).

RES with its traditional co-existence of laboratory and field research constituted such a border area, and the emergence of statistics reshaped the cultural terrain that connected field experiments and laboratory practices at the agricultural institution. This process was not a mere addition of statistical expertise, but involved a reshaping of tools, practices and institutional arrangements, the acquisition of the new mathematical and computing skills provided by statisticians, and their alliance with the Rothamsted experimental scientists in order to increase the accuracy of the station experiments.

With the analysis of variance it was possible to isolate the influence of several factors in field experiments, thus reducing in principle the complex field phenomena to a series of single causes investigations in agreement with the philosophy pursued in laboratory research. Statistics thus aligned field practice to laboratory standards, while paying due respect to the complexity of nature (RES, 1925, p. 15). On the other hand the methods that Fisher devised suited as well the needs of the laboratory investigations and statistics became an instrument for promoting higher precision in all the research done at Rothamsted.

[65] The classical experiments were preserved from the economies to be made at Rothamsted. For the replicated (annual experiments) it was instead decided in 1937 to limit the number of the experimental plots (RES, Extract from minutes of the Sub-Committee of the Field Plots Committee, 24th May 1937, Restriction of Experimental Program, RRes, FX 1.2 1933–1943).

In agricultural science higher experimental precision was not a goal in itself, but was intrinsically linked to the practical aims that agricultural science had traditionally been developed to serve and that justified funding for its research and education facilities (Harwood, 2005, Chap. 8). In the nineteenth century the quest for precision in agricultural research had been inspired by chemistry, while at the turn of the twentieth century it was the raising discipline of statistics to promise more precise and useful experimental results.

The development of analysis of variance and experimental design offers, therefore, an insight into the ''practical demands'' associated with statistical theory in the early decades of the twentieth century. Such practical demands gained a forum for discussion in 1930s Britain following the constitution of the Industrial and Agricultural Research Section of the Royal Statistical Society.[66] Agricultural science featured prominently in the section due to the success that analysis of variance and experimental design had gained since the 1920s, successes that extended well beyond agricultural research.

By the end of the 1950s, in fact, Fisher's methods had come to stay in psychology, sociology, education, chemistry, medicine, engineering, economics, quality control, just to mention a few of the disciplines which adopted them (Gigerenzer et al., 1989, pp. 114–115, 118). In all these fields it would be interesting to know how statistics reshaped tools, practices, institutional relations, and strategies for computing and data management. From such accounts can emerge a completely new perspective on the role of statistics in experimentation.

Acknowledgements

I thank Staffan Müller-Wille for multiple readings and helpful suggestions on earlier drafts of this paper, which is based on my PhD thesis. Portions of this work were discussed in the seminar series of the International Centre for the History of Universities and Science in Bologna (2010) and at the annual conference of the British Society for the History of Science (2011). I thank the audiences of both events for their comments and advice. Helpful suggestions from two anonymous referees improved further the original draft. A PhD scholarship in Science,

[66] Paradoxically the first author who drew attention to the relevance of agriculture and industry as contexts for the development of statistical theory in twentieth century Britain was Mackenzie, 1981, p. 213. On the Industrial and Agricultural Section see Anonymous, 1934.

Technology, and Humanities from the University of Bologna made the research for this paper possible. I am grateful to the Library and Archive of Rothamsted Research and to the Iowa State University Library for permission to quote from their collections.

Appendix: Staff of the Rothamsted Statistics Department, 1919–1933

See Tables 1, 2, 3.

Table 1. Statisticians

Name	Appointment
Ronald Fisher	1919–1933 (Head of Department)
	1933–1939 (Honorary Consultant)
Winifred Mackenzie	1920–1927
John Wishart	1927–1930
Joseph Irwin	1928–1930
Margaret Webster	1930–1933
Frank Yates	1931–1968

Sources RES, *Reports*, *1919–1968*

Table 2. Assistant staff

Name	Appointment
W. D. Christmas (honorary)	1921–1931
A. D. Dunkley	1922–1932
Kathleen Abbott	1924–1927
Florence Pennells	1927–1938
Alice Kingham	1929–1930
Kitty Rolt	1929–1936
J. M. West	1933–1934
Margaret Dunckley	1933

Sources RES, *Reports*, *1919–1938*

Table 3. Visiting workers

Name	Period	Institution and sponsorship
E. Somerfield	Dec. 1922–Apr. 1923	Assistant of W. S. Gosset, Guinness Brewery, Dublin
L. H. C. Tippett	1923–1925	British Cotton Industries Research Association (Shirley Institute, Manchester)
J. E. James	1926	Colonial Office
T. N. Hoblyn	1925–1926	East Malling Research Institute
(Prof.) B. Balmukand	Oct. 1927–Jul. 1928	Agricultural College Lyallpur, Bengal
A. J. Page	Oct. 1927–1928	I.C.S., Burmah
D. W. Boehme	June–Aug. 1928	Halle
W. H. Beckett	Sept.–Oct. 1928	Assistant Superintendent, Department of Agriculture, Acra, Gold Coast
J. B. Hutchinson	1928	Empire Cotton Research Station, Trinidad
H. Hotelling	June–Dec. 1929	Stanford University, California
H. G. Sanders	1929	–
B. P. Scattergood (honorary)	1927–1929	–
J. Pepper	Aug.–Sept. 1929	Postgraduate student at University College London
G. W. Nye	Aug.–Sept. 1929	Agricultural Department, Campala, Uganda
W. G. Eggleton	Sept.–Oct. 1929	Agricultural Advisory Department, Imperial Chemical Industries
R. J. Kalamkar	Sept. 1929–Apr. 1932	Nagpur University, Central Provinces, India
Frances E. Allan	Oct. 1929–July 1930	University of Melbourne. Studentship from Council for Scientific and Industrial Research, Melbourne
H. W. Jack	Nov. 1929	Economic Botanist Agricultural Department, Kuala Lumpur
J. W. Hopkins	1930–1932	University of Alberta, Edmonton, Canada
C. H. N. Jackson	Jan.–Feb. 1930	Zoologist, Tsetse Research Laboratory, Tanganyika Territory
E. Anderson	Feb. 1930; Sept. 1930	Missouri Botanical Garden (sponsored by the Rockefeller Foundation)
H. C. Arnold	May 1930	Agricultural Department Salisbury, Rhodesia
(Prof.) A. de Oliveira Franco	May–June 1930	Chief of Technical Section, Bureau of Cotton, Ministry of Agriculture, Rio de Janeiro, Brazil
B. Christidis	July 1930	Plant Breeding Station, Salonika

Table 3. continued

Name	Period	Institution and sponsorship
C. H. Goulden	July–Aug. 1930	Dominion Rust Research Laboratory, Manitoba Agricultural College, Winnipeg
A. W. R. Joachim	Sept.–Oct. 1930	Department of Agriculture, Ceylon
A. L. Murray	Oct. 1930–Apr. 1931	Assistant of W. S. Gosset, Guinness Brewery, Dublin
F. R. Immer	Oct. 1930–June 1931	Associate geneticist, U.S. Department of Agriculture, University Farm, St. Paul, Minnesota (Rockefeller Foundation Fellowship)
(Prof.) R. F. Summerby	Feb.–June 1931	Agronomy Department, MacDonald College, Quebec
S. H. Justensen	Mar.–June 1931	The University, Wageningen, Holland
H. R. Hoskins	Apr. 1931	Serere Experiment Station, Uganda
J. T. Campbell	July 1931	Fellowship from University of New Zealand
F. Billington	July–Aug. 1931	–
H. B. Bescoby	Sept. 1931	Wye Agricultural College
H. J. Buchanan-Wollaston	Nov. 1931	Fisheries Laboratory, Lowestoft
T. Eden	1932	Tea Research Institute, Ceylon
H. B. Bescoby	1932	Wye Agricultural College
S. A. Stouffer	Apr.–Aug. 1932	Department of Sociology, University of Wisconsin, Madison
R. O. Iliffe	May–July 1932	Agricultural Research Institute, Coimbatore, India
R. S. Koshal	May 1932–May 1933	Senior Research Assistant, Technical Research Laboratory, Bombay
I. Bachér	July–Sept. 1932	Agricultural Department, Central Experiment Station, Stockholm, Sweden
P. E. Turner	July; Sept. 1932	Imperial College of Agriculture, Trinidad
J. Rasmussen	July–Aug. 1932	Seed Breeding Station, Lund University, Svalöf, Sweden
C. Stuart Christian	Oct. 1932–Mar. 1933	Department of Genetics, Division of Plant Industry, Queensland University Brisbane (Fellowship from Council of Scientific and Industrial Research, Australia)
R. K. S. Murray	Nov. 1932	Rubber Research Scheme, Neboda, Ceylon
R. A. Taylor	Nov–Dec. 1932	St. Andrews
A. Bigot	Jan.–May 1933	Agricultural High School, Wageningen, Holland, scholarship L. E. B. Foundation

Table 3. continued

Name	Period	Institution and sponsorship
R. A. Scott	Feb–May 1933	Department of Agriculture, Launceston, Tasmania
S. S. Wilks	Jan.–Apr. 1933	Columbia University, New York
H. L. G. Milne	May–July 1933	Department of Agriculture, Entebbe, Uganda
J. B. Hutchinson	(previous stay in 1928) May–June 1933	Institute of Plant Industry, Indore, Central India
A. P. Malan	July–Sept. 1933	School of Agriculture, Cambridge. Previously University of S. Africa
I. Zacopanay	1933–1934	–
A. V. Coombs	1933–1934	Appointed to work with Imperial Chemical Industries at Colombo, Ceylon

Sources RES, *Reports*, 1919–1933; *Records of the Rothamsted Staff Harpenden*, 1929–1935; RRes, STA 2.1; List of Fisher's voluntary workers at Rothamsted prepared by Hall, 2007, pp. 321–322

References

Aldrich, John. 2007. "Variance, Analysis of Variance and ANOVA." In *Earliest known uses of some of the words of mathematics*, http://jeff560.tripod.com/v.html [accessed 9th April 2014].

Anonymous. 1934. "Note on the Formation of the Industrial and Agricultural Section of the Royal Statistical Society." *Supplement to the Journal of the Royal Statistical Society* 1: 1–3.

Brassley, Paul. 1995. "Agricultural Research in Britain, 1850–1914: Failure, Success and Development." *Annals of Science* 52: 465–480.

—— 2004–2008. "Hall, Sir (Alfred) Daniel (1864–1942)." *Oxford Dictionary of National Biography*. Oxford: Oxford University Press.

Briggs, G.E., Canny, M.J.P. and Barker, J. 1961. "Ernest John Maskell, 1895–1958." *Biographical Memoirs of Fellows of the Royal Society* 7: 161–171.

Campbell-Kelly, Martin, Croarken, Mary, Flood, Raymond and Robson, Eleanor (eds.). 2003. *The History of Mathematical Tables: From Sumer to Spreadsheets*. Oxford: Oxford University Press.

Charnley, Berris. 2011. *Agricultural Science, Plant Breeding and the Emergence of a Mendelian System in Britain, 1880–1930*. Doctoral Dissertation, University of Leeds.

Clarke, E. [rev. A. E. Johnston]. 2004–2008. "Gilbert, Sir Joseph Henry (1817–1901)." *Oxford Dictionary of National Biography*. Oxford: Oxford University Press.

Cochran, William G. 1976. "Early Development of Techniques in Comparative Experimentation." D.B. Owen (ed.), *On the History of Statistics and Probability*. New York: Marcel Dekker Inc., pp. 3–25.

—— 1980. "Fisher and the Analysis of Variance." S.E. Fienberg and D.V. Hinkley (eds.), *R. A. Fisher: An Appreciation*. Berlin: Springer, pp. 17–34.

Croarken, Mary. 2003. "Table Making by Committee: British Table Makers, 1871–1965." Martin Campbell-Kelly, Mary Croarken, Raymond Flood and Eleanor Robson (eds.), *The History of Mathematical Tables: From Sumer to Spreadsheets*. Oxford: Oxford University Press, pp. 235–263.

Crowther, E.M. 1936. "The Technique of Modern Field Experiments." *Journal of the Royal Agricultural Society of England* 97: 54–81.

Eden, Thomas. 1935. "The Development of Field Experiments in Agricultural Research." *Tropical Agriculturist* 84(63–69): 131–149.

Fisher, Ronald A. 1918. "The Correlation Between Relatives on the Supposition of Mendelian Inheritance." *Transactions of the Royal Society of Edinburgh* 52: 399–433.

—— 1925. *Statistical Methods for Research Workers*, 1st ed. Edinburgh: Oliver and Boyd.

—— 1926. "The Arrangement of Field Experiments." *Journal of the Ministry of Agriculture* 33: 503–513.

—— 1931. "Principles of Plot Experimentation in Relation to the Statistical Interpretation of the Results." In *Rothamsted Conferences XIII, The Technique of Field Experiments*, pp. 11–13.

—— 1934. "The Contributions of Rothamsted to the Development of the Science of Statistics." *Report 1933*, Rothamsted Experimental Station. St. Albans: Gibbs and Bamforth, pp. 43–50.

—— 1946. *Statistical Methods for Research Workers*, 10th ed. Edinburgh: Oliver and Boyd.

—— 1947. *The Design of Experiments*, 4th ed. Edinburgh: Oliver and Boyd.

—— 1953. "The Expansion of Statistics." *Journal of the Royal Statistical Society A* 116: 1–10.

Fisher, Ronald A. and Mackenzie, Winifred A. 1923. "Studies in Crop Variation II: The Manurial Response of Different Potato Varieties." *Journal of Agricultural Science* 13: 311–320.

Fisher, Ronald A. and Wishart, John. 1930. *The Arrangement of Field Experiments and the Statistical Reduction of the Results*. Imperial Bureau of Soil Science Technical Communication No. 10, 23 pp.

Fisher, Ronald A. and Yates, Frank. 1938. *Statistical Tables for Biological, Agricultural and Medical Research*. Edinburgh: Oliver and Boyd.

Fisher Box, Joan. 1978. *R. A. Fisher: The Life of a Scientist*. New York: Wiley.

Fussell, G.E. 1935. "The Technique of Early Field Experiments." *Journal of the Royal Agricultural Society of England* 96: 78–88.

—— 1976. "Agricultural Science and Experiment in the Eighteenth Century: An Attempt at a Definition." *The Agricultural History Review* 24: 44–47.

Gigerenzer, Gerd, Swijtink, Zeno, Porter, Theodore, Daston, Lorraine, Beatty, John and Krüger, Lorenz. 1989. *The Empire of Chance*. Cambridge, MA: Cambridge University Press.

Gosset, William S. 1962. *Letters from W. S. Gosset to R. A. Fisher, 1915–1936*. Dublin: Printed for Private Circulation by Arthur Guinness and Sons.

Grier, David A. 2007. *When Computers Were Human*. Princeton: Princeton University Press.

Hagen, Joel B. 2003. "The Statistical Frame of Mind in Systematic Biology from 'Quantitative Zoology to Biometry'." *Journal of the History of Biology* 36: 353–384.

Hald, Anders. 1998. *A History of Mathematical Statistics from 1750 to 1930*. New York: Wiley.

—— 2007. *A History of Parametric Statistical Inference from Bernoulli to Fisher, 1713–1935*. New York: Springer.

Hall, Alfred D. 1909. "The Experimental Error in Field Trials." *The Journal of the Board of Agriculture* 16: 365–370.

—— 1931. "Chairman's Opening Remarks." *Rothamsted Conferences XIII, The Technique of Field Experiments*, p. 9.

Hall, Nancy S. 2002. *R. A. Fisher and Randomized Experimental Design*. Doctoral Dissertation, University of Maryland, College Park.

—— 2007. "R. A. Fisher and His Advocacy of Randomization." *Journal of the History of Biology* 40: 295–325.

Harwood, Jonathan. 2005. *Technology's Dilemma*. Bern: Peter Lang.

Higgs, Edward. 1996. "The Statistical Big Bang of 1911: Ideology, Technological Innovation and the Production of Medical Statistics." *Social History of Medicine* 9: 409–426.

Horsburgh, E.M. (ed.). 1914. *Handbook of the Exhibition of Napier Relics and of Books, Instruments and Devices for Facilitating Calculation*. Edinburgh: Royal Society of Edinburgh.

Johnston, A.E. 1994. "The Rothamsted Classical Experiments." R.A Leigh and A.E. Johnston (eds.), *Long-Term Experiments in Agricultural and Ecological Sciences*. Wallingford: CAB International, pp. 9–37.

Johnston, James F.W. 1849. *Experimental Agriculture*. Edinburgh: W. Blackwood and Sons.

Kohler, Robert E. 2002. *Landscapes and Labscapes*. Chicago: The University of Chicago Press.
Lehman, Eric L. 2011. *Fisher, Neyman and the Creation of Classical Statistics*. New York: Springer.
Mackenzie, Donald A. 1981. *Statistics in Britain, 1865–1930*. Edinburgh: Edinburgh University Press.
Martin, Ernst [English Translation by P. Aldrich Kidwell and M.R. Williams]. 1992. *The Calculating Machines*. Cambridge, MA: The MIT Press.
Maskell, Ernest J. 1929. ‘‘Experimental Error: A Survey of Recent Advances in Statistical Methods.’’ *Tropical Agriculture Trinidad* 5: 306–309; 6: 5–11, 45–48, 97–99.
Mazumdar, Pauline M.H. 2011. *Eugenics, Human Genetics and Human Failings: The Eugenics Society, Its Sources and Its Critics in Britain*. London: Routledge.
Mercer, W.B. and Hall, A.D. 1911. ‘‘The Experimental Error of Field Trials (with an Appendix by Student).’’ *The Journal of Agricultural Science* 4: 107–132.
Müller-Wille, Staffan. 2005. ‘‘Early Mendelism and the Subversion of Taxonomy: Epistemological Obstacles as Institutions.’’ *Studies in History and Philosophy of Biological and Biomedical Sciences* 36: 465–487.
Neyman, Jerzy. 1934. ‘‘On the Two Different Aspects of the Representative Method: The Method of Stratified Sampling and the Method of Purposive Selection.’’ *Journal of the Royal Statistical Society* 97: 558–625.
Pearson, Egon S. 1939. ‘‘Student as Statistician.’’ *Biometrika* 30: 210–250.
—— *Student: A Statistical Biography of William Sealy Gosset* (Edited and Augmented by R.L. Plackett with the Assistance of G.A. Barnard). Oxford: Clarendon Press.
Pirie, N.W. 2004–2008. ‘‘Russell, Sir (Edward) John (1872–1965).’’ *Oxford Dictionary of National Biography*. Oxford: Oxford University Press.
Porter, Theodore M. 1986. *The Rise of Statistical Thinking, 1820–1900*. Princeton: Princeton University Press.
—— 1996. *Trust in Numbers*. Princeton: Princeton University Press.
—— 2006. *Karl Pearson: The Scientific Life in a Statistical Age*. Princeton: Princeton University Press.
Provine, William B. 2001. *The Origins of Theoretical Population Genetics*. Chicago: The University of Chicago Press.
Reid, Constance. 1998. *Neyman*. New York: Springer.
Ross, Gavin. 2012. ‘‘Fisher and the Millionaire: The Statistician and the Calculator.’’ *Significance* 9(6): 46–48.
Rossiter, Margaret W. 1975. *The Emergence of Agricultural Science*. New Haven: Yale University Press.
Rothamsted Experimental Station. Undated. *Programme of Work at the Rothamsted Experimental Station for the Years 1919–1920*. Harpenden: Printed by D. J. Jeffery.
—— 1921. *Report 1918–1920 With the Supplement to the ‘Guide to Experimental Plots’*. Harpenden: Printed by D. J. Jeffery.
—— 1925. *Report 1923–1924 with the Supplement to the ‘Guide to Experimental Plots’*. Harpenden: Printed by D. J. Jeffery.
—— 1927. *Report 1925–26 with the Supplement to the ‘Guide to Experimental Plots’*. Harpenden: Printed by D. J. Jeffery.
—— 1929. *Report 1927–28 with the Supplement to the ‘Guide to Experimental Plots’*. Harpenden: Printed by D. J. Jeffery.
—— 1930. *Report for 1929*. Harpenden: Printed by D. J. Jeffery.
—— 1931. *Report for 1930*. St. Albans: Gibbs and Bamforth.

—— 1934. *Report for 1933*. St. Albans: Gibbs and Bamforth.

—— 1962. *Report of the Rothamsted Experimental Station for 1961*. Harpenden: Rothamsted Experimental Station.

Rothamsted Research. 2006. *Guide to the Classical and Other Long-Term Experiments, Datasets and Sample Archive*. http://www.rothamsted.ac.uk/sites/default/files/attachments/2013-10-25/LongTermExperiments_small.pdf [accessed 8th April 2014].

Russell, E. John. 1935. "Rothamsted in 1933–1934." *Records of the Rothamsted Staff Harpenden* 5: 7–9.

—— 1956. *The Land Called Me*. London: George Allen and Unwin.

—— 1966. *A History of Agricultural Science in Great Britain, 1620–1954*. London: George Allen and Unwin.

Salvage, Leonard J. 1976. "On Re-Reading R. A. Fisher." *The Annals of Statistics* 4: 441–500.

Stigler, S.M. 1986. *The History of Statistics: The Measurement of Uncertainty Before 1900*. Cambridge, MA: Harvard University Press.

Street, Deborah J. 1990. "Fisher's Contributions to Agricultural Statistics." *Biometrics* 46: 937–945.

Student (alias W. S. Gosset). 1908. "The Probable Error of a Mean." *Biometrika* 6: 1–25.

—— 1923. "On Testing Varieties of Cereals." *Biometrika* 15: 271–293.

Swijtink, Zeno G. 1994. "Probability and Statistics in Agronomy." I. Grattan-Guinness (ed.), *Companion Encyclopedia of the History and Philosophy of the Mathematical Sciences 2*. London and New York: Routledge, pp. 1363–1369.

Thompson, F.M.L. 2004–2008. "Lawes, Sir John Bennet, First Baronet (1814–1900)." *Oxford Dictionary of National Biography*. Oxford: Oxford University Press.

Upton, G. and Cook, I. 2008. "Tukey, John Wilder." *A Dictionary of Statistics*, 2nd ed. Oxford: Oxford University Press.

Weston, B. 1962. *Fifty Years at Rothamsted, 1910–1960*. Privately Printed.

Wood, T.B. and Stratton, F.J.M. 1910. "The Interpretation of Experimental Results." *The Journal of Agricultural Science* 3: 417–440.

Yates, Frank. 1951. "The Influence of *Statistical Methods for Research Workers* on the Development of the Science of Statistics." *Journal of the American Statistical Association* 46: 19–34.

—— 1960. "The Use of Electronic Computers in the Analysis of Replicated Experiments, and Groups of Experiments of the Same Design." *Bulletin de l'Institut Agronomique et des Stations de Recherches de Gembloux, Hors série* 1: 201–210.

—— 1990. "Foreword." Ronald A. Fisher (ed.), *Statistical Methods, Experimental Design and Scientific Inference*. Oxford: Oxford University Press, pp. vii–xxxii.

Yates, JoAnne. 2008. *Structuring the Information Age: Life Insurance and Technology in the Twentieth Century*. Baltimore: The John Hopkins University Press.

Young, Arthur. 1770. *A Course of Experimental Agriculture I*. London: J. Dodsley.