Liebig and the Rothamsted experiments

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1 Introduction

In this contribution to the celebration of the 150th anniversary of the publication of the first edition of Justus Liebig's book on "Chemistry in its application to Agriculture and Physiology" I want to show how Liebig changed his ideas on some aspects of plant nutrition between the first and third edition of his book published in 1840 and 1843 respectively. Principal amongst these was his suggestion about the source from which plants derive their nitrogen. In the first edition he discussed how plants derive their nitrogen via the soil and continued by suggesting that atmospheric inputs of ammonia were not sufficient for the purposes of agriculture. By the third edition he had decided that atmospheric inputs were sufficient. Lawes and Gilbert's results from 1843 onwards in their field experiments at Rothamsted clearly supported the ideas of the first edition but not of the third. Thus from 1843 onwards there developed a most acrimonious controversy between Liebig and Lawes & Gilbert which rumbled on for 20 years or so. I hope to show a little of how it developed. In part Lawes & Gilbert continued their field experiments to demonstrate the need to apply readily available nitrogen to soils to achieve good yields of agricultural crops. Some of these experiments still continue and I also want to demonstrate the need for long-term experiments in agricultural research.

2 The people involved

In the comparatively small scientific community of Western Europe in the early 1800s scientists were probably better known to those working in other disciplines than they are today. In the late 1830s and early 1840s there were a number of scientists through whom it is possible to trace various links between Liebig and Lawes & Gilbert. On this occasion it is perhaps appropriate to say a little about some of them and the parts they played. Mention is made chiefly of British scientists because they will be less well known to those in Germany who have followed Liebig's scientific career in detail.

2.1 Justus Liebig, * 1803 †1873

Professor of Chemistry first at Giessen (1824–52) then at Munich (1852–73) Liebig was undoubtedly one of the most brilliant chemists of his generation. It should not be forgotten that because of his acknowledged eminence he was invited by the British Association for the Advancement of Science (BA) to prepare "a report upon the state of organic chemistry". The first edition of the book, whose publication in 1840 we celebrate, was but a part of that report. The second part published as "Chemistry in its application to Physiology and Pathology" came two years later.

The following quotation is taken from the preface to the first book. *"I shall be happy if I succeed in attracting the attention of men of science to subjects which so well merit to engage their talents and energies. Perfect agriculture is the true foundation of all trade and industry - it is the foundation of the riches of states. But a rational system of agriculture cannot be formed without the application of scientific principles; for such a system must be based on an exact acquaintance with the influence of soils and the action of manure upon them."*

The report certainly attracted the attention of scientific men interested in the rational pursuit of agriculture. In fact the interest engendered in the application of science to agriculture has today manifested itself in the apparent overproduction of food in parts of the developed world although globally many go hungry. Perhaps the current problems of the Common Agricultural Policy within the European Community can be laid at Liebig's door!

The following three quotations are taken from the first edition:

1. *"We have not the slightest reason for believing that nitrogen of the atmosphere takes part in the processes of assimilation of plants and animals. ...But...numerous facts show that the formation in plants of substances containing nitrogen, such as gluten, takes place in proportion to the quantity of this element which is conveyed to their roots in*

the state of ammonia..."

2. *"It will in a subsequent part of this work be shown that the last products of the decay and putrefaction of animal bodies present themselves in two different forms. They are in the form of a combination of hydrogen and nitrogen - ammonia, in the temperate and cold climates, and in that of a compound, containing oxygen, nitric acid, in the tropics and hot climates. The formation of the latter is proceeded by the production of the first. Ammonia is the last product of the putrefaction of animal bodies; nitric acid is the product of the transformation of ammonia."*

3. *"No conclusion can then have a better foundation than this, that it is the ammonia of the atmosphere which furnishes nitrogen to plants."*

Clearly Liebig had remarkable insight or intuition!

2.2 Lyon Playfair, * 1818 †1898

Contemporary in age with Lawes & Gilbert, Lyon Playfair started studying medicine in 1832 but abandoned his studies because of ill health. After a brief period of recuperation he returned to science. He had the good fortune to work at Giessen when Liebig was at the height of his fame as a scientific investigator and teacher and had begun to turn his attention to the application of organic chemistry to agriculture. Playfair was awarded his doctorate for work with Liebig during 1839–40. He also helped with the preparation of Liebig's report to the BA at Glasgow in 1840 and presented it there as Liebig's representative. He helped prepare the English edition of the book although it is clear that Liebig had a good command of English. Although he discovered the nitroprussides and worked with both Joule and Bunsen, Playfair became essentially a scientific administrator, one of his first appointments was as a special commissioner for the Great Exhibition in London in 1851.

As both an active member of the BA, with its strong links to science, and as Consultant Chemist to the Royal Agricultural Society of England (RASE) with its association with farming, Playfair probably appreciated more than many others the ever widening gulf that developed between Liebig and Lawes & Gilbert on the sources from which plants derive their nitrogen (see later). Correspondence between Gilbert and Playfair shows that he attempted to act as mediator between Liebig and Lawes & Gilbert and tried to get them to meet at the BA meeting in Glasgow in 1855. In a letter to Gilbert, Playfair commented that *„Now as to your remarks about personalities. Liebig only uses them when he has the pen in his hand. - I suppose the gall in the ink produces them for in conversation and viva voce discussion he is the most amicable and good natured of men.“*.

2.3 Thomas Graham, * 1805 †1869

Graham was appointed to a Chair in Chemistry at University College, London in 1837. Lyon Playfair was a pupil of his at Glasgow and then worked as his assistant in London before going to Giessen. Lawes too had worked at University College, in the laboratories of Professor Anthony Todd Thompson, first holder of the Chair of Materia Medica, Therapeutics and Toxicology and founder of the British Pharmacopoeia. Lawes must have made Graham's acquaintance, in fact he may well have discussed phosphorus chemistry with him because Graham was a world authority in this field at that time. It was Graham who in December 1843 wrote on Lawes' behalf to Liebig asking him to receive Lawes. Unfortunately the brief letter simply says that:"He (Lawes) will himself explain the sort of information he is in need of."Graham and Liebig maintained their friendship for it was Graham who, in 1854, arranged for British scientists to present a "testimonial" to Liebig to mark his appointment to the Chair at Munich.

2.4 John Joseph Mechi, * 1802 †1880

Mechi was nearer in age to Liebig and Graham than to Lawes & Gilbert. He was an inventor and business man. Between 1830 and 1840 he made a considerable fortune from the "magic razor strop" which bore his name and was used to sharpen safety razor blades. In 1841 he purchased a farm of 53 hectares at Tiptree Heath, a very unproductive part of Essex. He wrote much about English farming and how to make it profitable. A folder of letters in the Rothamsted archive shows that he corresponded frequently with Liebig in the early 1860s. He appears to have accepted many of Liebigs's ideas especially on the use of town sewage and its deep incorporation into soil. It was in this correspondence that Liebig made some spiteful comments about Lawes and Gilbert and the Royal Agricultural Society of England (RASE). Although the fallacy of Liebig's later writings on the source of nitrogen for plants is now accepted, there were those at the time of the third and subsequent editions of his book who accepted his teachings. Perhaps it is somewhat unfair to draw too many inferences but Liebig's faithful disciple at Tiptree Farm had many poor harvests after 1866 which eventually lead to his affairs being put into liquidation just before his death in 1880.

2.5 John Bennet Lawes, * 1814 †1900

Although Lawes was a boy at Eton and an undergraduate at Oxford he appears to have found little to stimulate an inquisitive scientific mind at either place. Leaving Oxford without a degree he returned to the Manor House at Rothamsted and had a chemical laboratory built in the best bedroom. He grew many medicinal plants, including some hectares of opium poppies on Rothamsted Farm and worked on their active principals.

Like many landowners he was well aware of the benefits that many farmers in Britain were finding from applying crushed bones to their land. Such was the trade in bones that the Britsh were accused of raping the battlefields of Europe to satisfy the demand! But bones were not effective on all soils - they weren't at Rothamsted. Like others, Lawes treated the bones with sulphuric acid - making superphosphate of lime which was effective on most soils. Lawes was granted a patent for superphosphate manufacture using bones and various other forms of mineral (rock) phosphates. He built the world's first fertilizer factory beside the Thames at Deptford in 1842. His first advertisement for his patent mineral manures appeared in the Gardener's Chronicle in 1843: It is interesting to compare its simplicity with the glitzy advertising of today. Lawes built a second factory at Barking in 1857 and then in 1872 sold the business for £300 000, equivalent to £10 000 000 now. In 1889 Lawes created the Lawes Agricultural Trust with an endowment of £100 000. The Trustees, and a Committee of expert scientists and agriculturalists appointed to advise them, were effectively charged with ensuring that agricultural research should endure at Rothamsted.

2.6 Joseph Henry Gilbert, * 1817 †1901

As a boy, Gilbert had, according to his mother, only three interests, "electricity, arithmetic and chemistry". He studied chemistry first at Glasgow then at University College, London. After graduating he also worked first

Gardener's Chronicle July 1st, 1843

GUANO ON SALE, as Imported, of first quality, and in any quantity, direct from the bonded stores, either in Liverpool or London. Also, NITRATE of SODA, Apply to H. ROUNTHWAITE & Co., Merchants, 6 Cable-street, Liverpool.

J. B. LAWES'S PATENT MANURES, composed of Super Phosphate of Lime, Phosphate of Ammonia, Silicate of Potass, &c., are now for sale at his Factory, Deptford-creek, London, price 4s. 6d. per bushel. These substances can be had separately; the Super Phosphate of Lime alone is recommended for fixing the Ammonia of Dung-heaps, Cesspools, Gas Liquor, &c. Price 4s. 6d. per bushel.

M'Intosh's New Edition of the

PRACTICAL GARDENER, in ONE VOLUME, containing the latest and most approved modes of Management of KITCHEN, FRUIT, and FLOWER-GARDENS, GREEN-HOUSE, HOTHOUSE, CONSERVATORY, &c.; comprising numerous explana-

with Anthony Todd Thompson and first met Lawes during this period. In 1840 he also went to Giessen and, like Playfair and Augustus Voelcker, he went on to gain his doctorate with Liebig. In those days it would appear that the award of a doctorate was based on different criteria to those of today because at the end of 1840 Gilbert returned to England to work at University College during 1840–41. He then went into industry in Manchester. Because Lawes decided that he could not be both an agricultural experimenter and a business man during the early, formative years of his business, he decided to employ a full-time scientist and appointed Gilbert.

2.7 Lawes & Gilbert

Gilbert took up his appointment on 1 June 1843 the start of one of the longest (57 years) and most productive scientific partnership on record. In agricultural circles their names are forever linked and together they are regarded as the founding fathers of the scientific method in agriculture. Their skills and characters were totâlly complementary. Lawes was the more versatile and quick to see what the farmer wanted, he was always able to respond with sound practical and economic advice based on the results of the Rothamsted experiments. But the quality of the results emanating from the experiments owed much to Gilbert. Everything he undertook was performed with scrupulous accuracy and meticulous care to detail. Long after his death a badly performed piece of work whether in the field or the laboratory would bring forth the admonition "you know Sir Henry wouldn't have that" from the Superintendent trained by Gilbert and then entrusted to carry on as the master had decreed. Gilbert indeed gave scientific expression to the work of Rothamsted and established the field experiments on a sound scientific basis.

3 The controversy between Lawes & Gilbert and Liebig

It is worthwhile to briefly recall the order in which some of the events of interest occured. Liebig's report was presented to the BA meeting in Glasgow in September 1840 and the first edition of his book appeared that autumn. Lawes first published some results of his experiments, mainly in pots and related to the availability of phosphates, in 1841 in the Gardeners' Chronicle. Lawes was joined by Gilbert in June 1843 and the first field experiment on Barnfield , on the growth of turnips, was started in July. In the autumn of 1843 the first experimental wheat crop was drilled on Broadbalk. The initial experimental design was the same for both experiments - long narrow plots each testing one treatment. The subsequent changes to the Barnfield experiment, principally those made in 1856, which made it the most comprehensive of the experiments started by Lawes & Gilbert - the Classical experiments - were probably Gilbert's idea. Also in 1843 Liebig published the third edition of his book.

It can be assumed that Lawes was familiar with Liebig's work - the copy of the first edition in the Rothamsted archive belonged to him. Gilbert, having studied under Liebig, was probably well aware of Liebig's views on crop nutrition. However, Lawes & Gilbert must have had an open mind about the sources from which plants get their nutrients when they started the Barnfield and Broadbalk experiments. In both experiments nitrogen, phosphorus, potassium, sodium and magnesium were tested singly and in various combinations as simple chemical salts and their effects compared with those of farmyard manure (FYM).

The first harvest of turnips in 1843 and winter wheat in 1844 showed that both crops, but especially wheat, responded to a small amount of readily assimilable nitrogen applied to the soil as a simple salt of ammonium or nitrate. In fact Lawes & Gilbert never failed to point out that this occured even though the amount of N applied was minute relative to the total nitrogen content of the soil. It is also a tribute to Lawes' objectivity that he devoted so much effort to emphasizing the importance of nitrogen although he derived most of his income from the sale of superphosphate.

Returning to the first edition of Liebig's book. He clearly appreciated the cycling of nitrogen although he appears to have assumed that all the nitrogen in plants would pass to animals, including man, and that on their death, the nitrogen they contained would be released as ammonia to the atmosphere. He mentions that ammonia is very soluble in water and that ammonia would be returned to the surface of the earth in rainfall. He commented that his view would be difficult to test because of the deficiencies of available analytical techniques. Liebig estimated the amount of ammonia coming in in rainfall each year (see later) and the quantity is undoubtedly too large. But it could well have been a realistic estimate of the total amount of nitrogen being cycled. Clearly some of the ammonia he assumed going to the atmosphere would have been trapped in the soil solution, and some converted to nitrate, even in temperate climates. Some nitrogen, as nitrate, would also have been lost by leaching and denitrification.

His calculation was as follows: *"If a pound of rainwater contains only 1/4th of a grain of ammonia, then a field of 40,000 sq feet must receive annually upwards of 80 lb of ammonia or 65 lb of nitrogen. ...This is much more nitrogen than is contained in the form of vegetable albumen and gluten in 2650 lb of wood, 2800 lb of hay or 200 cwt of beet- root which are the yearly produce of such a field but it is less than the straw, roots and grain of corn which might grow on the same surface, would contain".*

What a small step it would have been then to have acknowledged Lawes & Gilbert's results on the effects of a small addition of ammonia on cereal yields. In fact, Liebig himself in the first edition had stated:

"Cultivated plants receive the same quantity of nitrogen from the atmosphere as trees, shrubs and other wild plants; but this is not sufficient for the purposes of agriculture."

Liebig was right in 1840 and the experimental results in 1843/44 from field-grown crops at Rothamsted were the proof he needed. Strangely, however, in the third edition in 1843, Liebig changed his mind and the quotation above was altered to:

"Cultivated plants receive the same quantity of nitrogen from the atmosphere as trees, shrubs and other wild plants; and this is quite sufficient for the purposes of agriculture."

The only reason for the change which I have been able to find was a comment Liebig made much later, *"But a series of observations, as well as continued reflection on the subject convinced me that this opinion (first edition) could not be maintained"* [Liebig, 1856].

One other example of the important changes between the first and third editions is worth noting. In the first edition Liebig wrote: *"When a field is manured with animal excrements, a smaller quantity of matter containing nitrogen is added to it than has been taken from it in the form of grass, herbs, or seeds. By means of manure, an addition only is made to the nourishment which the air supplies"* (namely ammonia).

In the third edition the last sentence was altered to: *"Therefore, it follows that the favourable activity of such manure cannot be due to its nitrogen"*.

Having made these and other major changes Liebig could not or would not go back to his original hypothesis. It says much for the high regard in which he was held for his contributions to chemistry that many men of science even in England continued to support his views on agricultural chemistry for many years. On the other hand many farmers quick to appreciate the value of extra yields from the use of nitrogen fertilizers followed Lawes & Gilbert.

Certainly the argument continued for many years often with great vehemence on Liebig's part. Many of the published milestones in the debate following the third edition in 1843 were in the Journal of the Royal Agricultural Society of England. One of the first was a paper by Lawes [Lawes, 1847]. Then in the third edition of his "Letters" published in 1851 Liebig wrote: *"With regard to the experiments of Mr. Lawes (the best authority according to Mr. Pusey) they are entirely devoid of value, as the foundation for general conclusions"*. [Liebig, 1851]

This attack led Lawes & Gilbert to reply in a paper, "On Agricultural Chemistry, especially in relation to the Mineral Theory of Baron Liebig" [Lawes & Gilbert, 1851]. In reply to that paper Liebig published, in the spring of 1855, a short treatise entitled „Principles of Agricultural Chemistry, with special reference to the late researches made in England"

[Liebig, 1855]. This was mainly a critical examination of the Rothamsted experiments. In it Liebig accused Lawes and Gilbert of not having read, of misunderstanding and of mistaking his views. He also asserted that Lawes & Gilbert "disproved that which they intended to prove; proved that which they intended to disprove" and considered that all their results confirmed the truth of his doctrines. Copies of these "Principles" were widely circulated in Europe and America and Lawes & Gilbert responded yet again. This time it was a very long and detailed paper [Lawes & Gilbert, 1855].

In their 1855 paper Lawes & Gilbert [Lawes & Gilbert, 1855] pointed out that at the BA meeting in 1854 an advocate of Liebig had suggested there had been a misunderstanding about nomenclature, claiming that salts of ammonia were mineral manures. This was disputed by Lawes & Gilbert and it seems to have been generally agreed that in the preceding ten or twelve years the term "mineral manure" had acquired an accepted significance designating those plant constituents which remain in the ash after incineration. And this was certainly the definition which had been adopted by Liebig from his continued separation of ammonical salts and mineral constituents.

Liebig [Liebig, 1856] quickly prepared and published a reply. It was about this paper that Lawes in a letter to Gilbert wrote, *"... and a more shuffling and equivocating production could not well be written"*.

Lawes also went on to say, *"I shall certainly decline to enter any further into the question of what he did say and what he now says but I should like if I could in the next journal to call attention to his present views and how far they differ from ours"*.

Nothing appeared in the next journal. And except in a rather long footnote (at p. 506) to their paper on manuring permanent meadowland Lawes & Gilbert [Lawes & Gilbert, 1863] made little further detailed reference in published papers to the controversy. They had little need to. The ever increasing weight of experimental evidence showed that their hypothesis was correct. Namely that it was the accumulation of available nitrogen within the soil itself which governed its fertility and that to achieve acceptable yields of agricultural crops the soil supply could be augmented by the judicious application of manures and fertilizers containing nitrogen in readily assimilable forms.

In retrospect it is obvious that the controversy was bedeviled by lack of a rigid nomenclature in a developing science. To some extent Liebig capitalised on this. He appears to have used the argument, put forward at the BA meeting in 1854, that ammonium salts were minerals to change his position. In 1862 he repudiated the classification of the ash constituents as unscientific and claimed ammonia and its salts as mineral manures [Liebig, 1862]. In a short paper published in 1864 he again accused Lawes and Gilbert of misinterpreting his classification of plant nutrient elements and the source from which plants derive them [Liebig, 1864]. Even in his letters to Mechi in the 1860s he was still claiming that he had always taught that ammonia was a mineral substance within his original definition.

Another practical aspect of Liebig's Mineral Theory is worth brief mention. Lawes & Gilbert were concerned that as Liebig expounded his theory he became more and more specific about the need only to replace the quantity of minerals removed in the ash of the harvested crop. This led, at least in Britain, to merchants offering various versions of Liebig's Patent Manure for a range of crops. The quantities of mineral nutrients supplied were small in relation to the overall fertility of many soils at that time. When tested in their experiments Lawes & Gilbert always found that compared with larger applications of phosphorus and potassium, the patent manure gave a smaller yield even though the same amount of nitrogen was applied to both treatments. This aspect of Liebig's Mineral Theory was also found therefore to be incorrect.

It is interesting that the first commercial producer of Liebig's Patent Manure was a Mr. Muspratt, a soda manufacturer from Liverpool. His son was a student of Liebig in 1843–45 and his daughter Emma visited Liebig and his family in Munich in 1854. Whilst there she became ill with cholera and was too ill to take food. Liebig prepared an extract of chicken meat by treating it with very dilute hydrochloric acid. This meat infusion saved the patient's life and subsequently that of many other seriously ill people.

4 The value of long–term experiments

Ten of the experiments started by Lawes and Gilbert between 1843 and 1883 still continue (Table 1). Some have had little change, some have been extensively modified to provide information relative to current farming practices. In many of the experiments the original fertilizer and farmyard manure treatments have remained unchanged. Thus the results can be used to determine how various husbandry systems affect soil fertility. This is vital information because a fertile soil is one of a country's most important natural resources. Fertility develops slowly over many decades but inept management can destroy it rapidly. Small, less obvious, but insidious changes can be equally damaging in the long–term. It is essential then that long–term experiments are made to quantify the effects of man's farming practices and anthropogenic activities on soil fertility. The rationale for long–term experiments must be that they

1. continue to supply data to improve farming practices;
2. are a resource capable of being exploited to better understand plant and soil processes, and
3. allow measurement of long-term changes.

It says much for Lawes & Gilbert's foresight that they kept samples of the crops grown each year on each treatment in a number of experiments.

Table 1: The ten experiments started by Lawes & Gilbert which still continue at Rothamsted.

Experiment name and year started	Priciple crops
Barnfield 1843	Turnips, mangolds, sugar beet.
Broadbalk 1843	Winter wheat.
Agdell 1848	Turnips, spring barley, legume, winter wheat.
Hoosfield 1852	Spring barley.
Exhaustion Land 1852	Winter wheat, potatoes, spring barley.
Garden Clover 1854	Red clover.
Park Grass 1856	Permanent grassland.
Alternate Wheat and Fallow 1856	Winter wheat.
Broadbalk Wilderness 1882	Natural regeneration of deciduous
Geescroft Wilderness 1886	woodland after winter wheat (Broadbalk) and field beans (Geescroft)

These samples still exist and have been added to continuously, they are a unique archive. Together with the experiments which still exist they are an unrivalled resource as the following examples aim to show in relation to the rationale for long-term experiments set out above.

It is also interesting to note that the value of long-term experiments in providing information on the effects of farming practices on soil properties is becoming ever more appreciated. A whole session was devoted to such experiments at the 1990 Congress of the International Soil Science Society at Kyoto, Japan. A number of papers were included from researchers seeking to increase food production in tropical areas.

5 Sustainability of yields

As mentioned earlier the Broadbalk experiment was started in the autumn of 1843 and winter wheat has been grown on all or part of each experimental plot each year since.

Figure 1 shows yields of the different cultivars grown since 1843 on two plots both given P, K, Mg fertilizers each year and one with no nitrogen, the other given 144 kg N/ha. Yields remained relatively stable on both plots until about 1910. They then declined because of competition from weeds which had previously been controlled by handhoeing. Yields recovered after the 1920s because fallowing one year in five was introduced to control weeds. Since the 1960s weedkillers have been used on nine-tenths of the experiment.

Between the 1890s and 1967 Squarehead's Master, or its close relative Red Standard, was grown each year and a number of eminent research workers have attempted to relate seasonal variation in yield to relatively simple meteorological observations. This has not proved possible even with data extending over 70 years [Yates, 1969]. This perhaps indicates how difficult it will be to assess "greenhouse effects" on crop production. In 1968 Cappelle Desprez was grown for the first time and since then new cultivars have been introduced when appropiate. Yields have continued to improve, the best now exceed the British national average. Throughout the experiment, yields on plots given 144 kg N/ha (with PK fertilizers) and those given 35 t/ha farmyard manure (FYM) annually have been essentially the same (Table 2).

The clear message form Broadbalk is that, on this soil and with this

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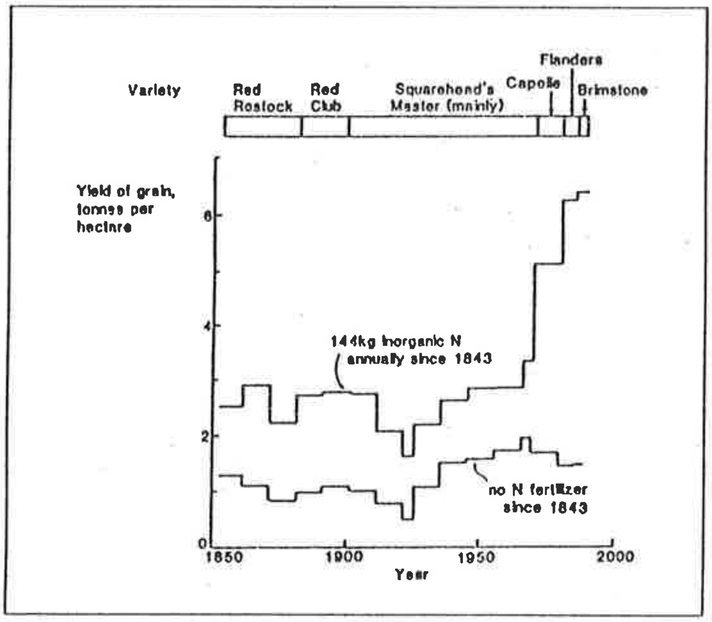


Figure 1: Change with time in the variety of winter wheat grown and the yield of grain on two plots on the Broadbalk experiment, Rothamsted. Both plots receive phosphorus, potassium, magnesium fertilizers each year; one gets no nitrogen, the other 144 kg N/ha each year.

Table 2: Yields of winter wheat, grain t/ha, given by fertilizers and farmyard manure on Broadbalk since 1852.

Period	Cultivar	144 kg N/ha plus P, K, Mg fertilizers	Farmyard manure 35 t/ha
1852–61	Red Rostock	2.52	2.41
1871-81	Red Rostock	2.23	2.04
1892–1901	Red Club	2.79	2.85
1902–11	Squarehead's Master	2.76	2.62
1935–44	Red Standard	2.61	2.61
1955–64	Squarehead's Master	2.84	2.97
1968–78	Cappelle Desprez	5.32	5.83
1979–84	Flanders	6.25	6.27
1985–89	Brimstone	5.78	5.79

husbandry, yields have not only been sustained but have increased appreciably even where fertilizers only have been used for about 150 years. This result has been much publicized but how far can the generalization be made to other soils? The experimental farm at Woburn, was started by the Royal Agricultural Society of England in 1876, it passed into Rothamsted's control in 1926. The soil is a sandy loam and experiment comparing NPK fertilizers and FYM for both winter wheat and spring barley grown continously were startetd in 1876. Irrespective of treatment, yields of both crops, but especially barley, declined dramatically over the next 50 years. In part this was because the soils became more acid but a build up of cereal cyst nematodes or free living nematodes could have contributed to the decline in yields, too [Johnston, 1991 a]. Recent research has suggested also that soil organic matter is important in maintaining the fertility of such light textured soils [Johnston, 1986, Johnston, 1991 b]. There is a major need for a better national/global coverage of long-term experimental sites.

6 Information of value to farming practices

Weedkillers were first used on Broadbalk in 1959 and weed control on the better yielding plots increases yield by as much as 1,5 t/ha grain. Such benefits can only be estimated in long-term experiments because the seed bank in both treated and untreated soils takes many years to stabilize. Since 1968, the plots have been further subdivided. It is now possible to compare yields of wheat grown continuously with those after a two-year break from cereals, a break of this length is usually sufficient to control soil-borne diseases. Figure 2 shows yields in two periods, 1970–78 and 1979–84. In the first period Cappelle Desprez was grown, in the second Flanders, these cultivars of winter wheat have only a small difference in

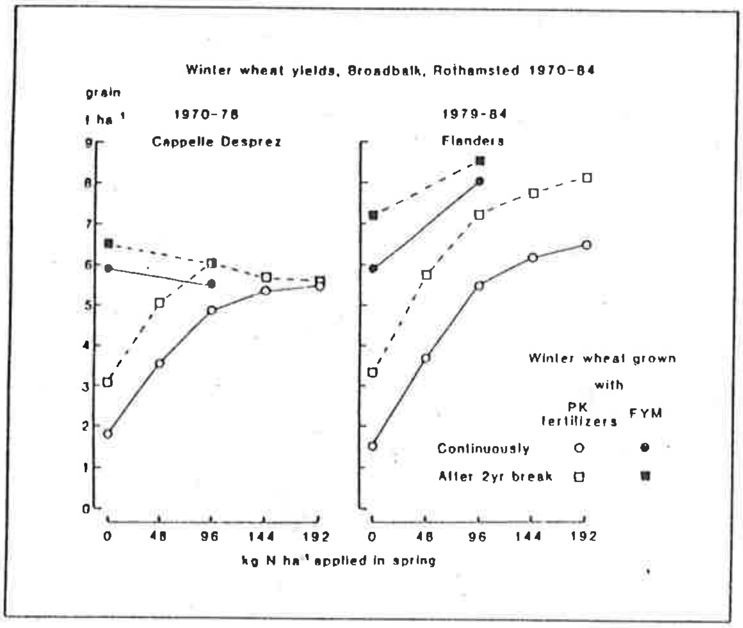


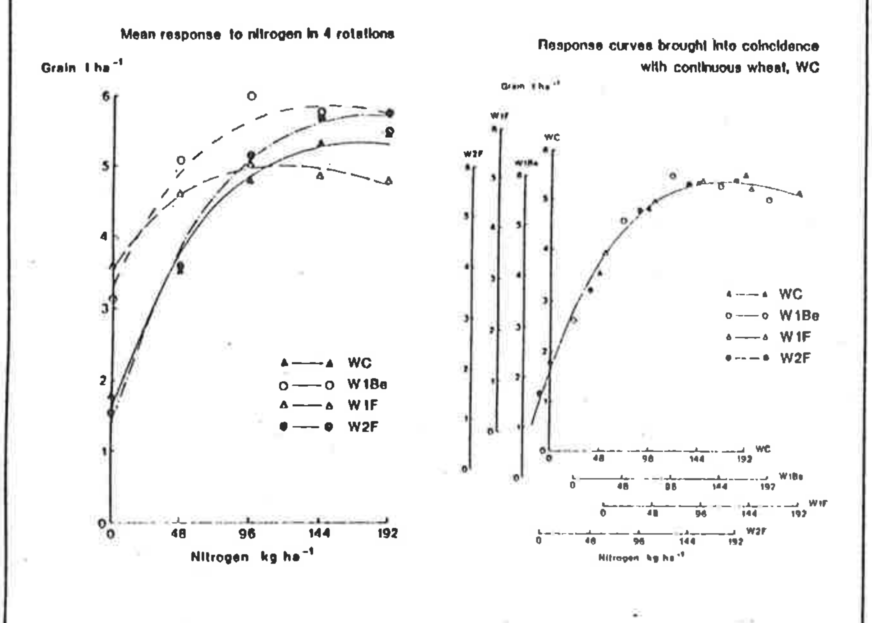
Figure 2: Average yields of winter wheat, grain t/ha, grown in 1970–78 and 1979–84 on Broadbalk at Rothamsted. [Dyke et al., 1983]

yield potential. When both were grown after a two-year break they invariably yielded more than when grown continuously. Farmers therefore would be advised to grow as many first wheats as possible in their rotations. The nitrogen response curves were very different in the two periods (Figure 2). There was little response above 96 kg/ha in the first period, but a much larger benefit from nitrogen applications exceeding 96 kg/ha in the second. In the second period fungicides were used regularly to control foliar pathogens especially mildew. Maintaining green leaf area and hence photosynthate supply during grain filling was important to achieve good yields and capitalize on the large inputs of nitrogen fertilizer. This was another important lesson for farmers.

7 A scientific resource

The response of winter wheat to nitrogen. During 1970–78 winter wheat was grown on Broadbalk in four rotations: as a first wheat after a two-year break; as a first and second wheat after a one year fallow and continuously. The four nitrogen response curves were very different (Figure 3, [Dyke et al., 1983]). The differences were difficult to explain especially as there is no rational biochemical or physiological explanation why wheat should respond to nitrogen in more than one way. It was, however, possible to fit reponse curves to the data using an exponential model with a linear term and derive both an optimum yield and its associated nitrogen dressing. Using appropriate horizontal and vertical shifts it was found that the four curves could be brought into coincidence (Figure 3b) - winter wheat did respond to nitrogen in the same way. The reason for the different curves for the four crops was because of the different amounts of available soil nitrogen, causing the need for horizontal shifts, and other factors needing vertical shifts. The latter probably included the effects of soil-borne pathogens and different amounts of foliar pathogens when fungicides were not used regularly.

Measuring and modelling changes in soil organic matter content. The organic matter or humus content of a soil depends on the amounts of organic matter added, the rate of decay of this organic matter and existing soil humus, soil texture and climate. The humus content of any soil moves towards an equilibrium value depending on these variables and changes tend to be slow in temperate climates. Figure 4 shows



a b

Figure 3: Effect of nitrogen on yields of winter wheat grown in four rotations: i Continuous wheat (WC); ii Wheat after beans (W1Be); iii First wheat after fallow (W1F); iv Second wheat afterfallow (W2F) on Broadbalk at Rothamsted 1970–78. Fig. 3a mean response to nitrogen in each rotation. Fig. 3b the four curves in 3a brought into coincidence by suitable horizontal and vertical shifts. [Dyke et al., 1983]

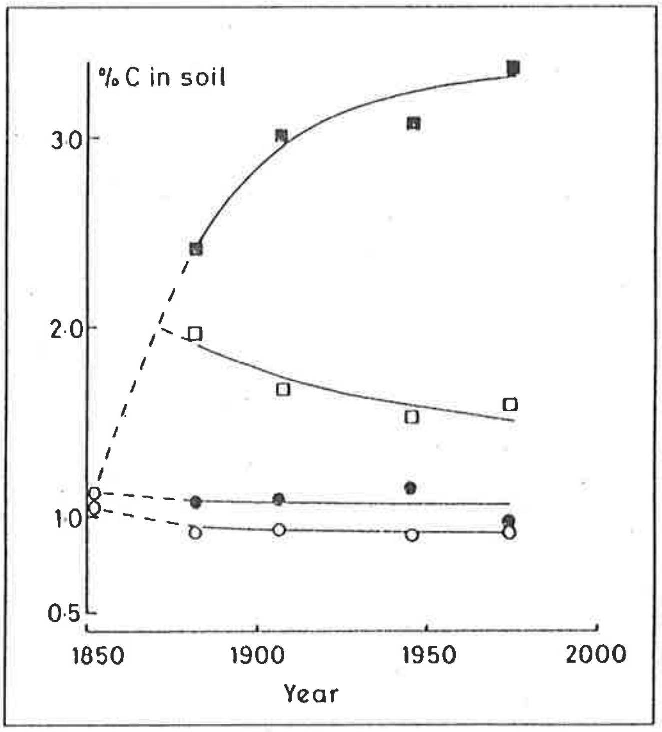


Figure 4: Changes with time in the carbon content of the Hoosfield Continuous Barley experiment soils at Rothamsted. Farmyard manure (FYM) 35 t/ha each year (■); FYM 35 t/ha each year 1852–71 none since (□); NPK fertilizers each year 48 kgN/ha (•); unmanured since 1852 (o). [Jenkinson & Johnston, 1977]

changes in soil carbon during 130 years on the Hoosfield experiment which was started in 1852 at Rothamsted [Jenkinson & Johnston, 1977]. Spring barley is grown each year. On unmanured soils and those given NPK fertilizers the organic matter content has remained essentially constant over the last 100 years. There is more organic matter in the soil given NPK fertilizers each year because larger crops were grown and more stubble and roots were returned each year. Where FYM (35 t/ha) has been applied each year soil humus content is still increasing albeit slowly now. Equally striking is the slow decline in humus content where FYM was given for the first 20 years and none since. These data have been used to model the rate of turnover of organic matter in soil.

Figure 5, taken from [Jenkinson et al., 1987], shows the good fit between modelled and measured values. Data from other long-term experiments under different climatic conditions and farming systems are now required to first validate and then widen the applicability of the model.

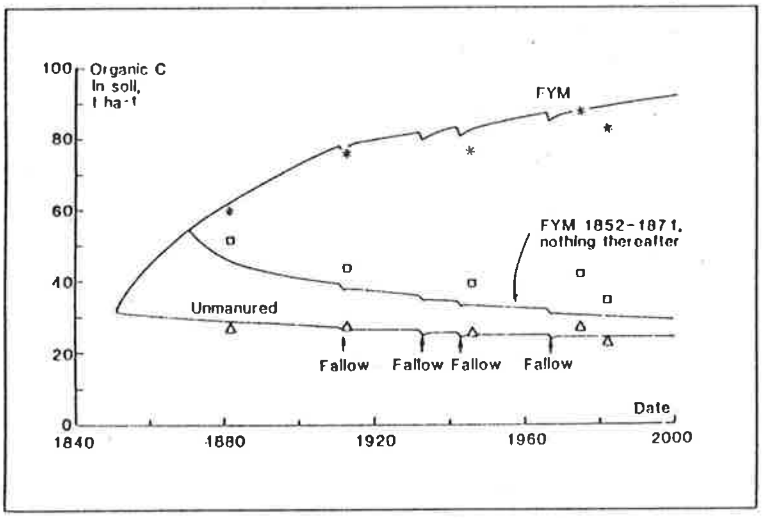


Figure 5: Organic carbon in the top 23 cm of soil in the Hoosfield Continuous Barley experiment. The symbols are the measured values from Figure 4, the lines represent the changing values derived from the carbon turnover model of [Jenkinson et al., 1987].

The importance of soil organic matter for crop production. In those Classical experiments in which annual applications of fertilizers and FYM are compared, soils receiving FYM now have about three times as much organic matter as those receiving fertilizers only. For the first 100 years or so yields on both soils were very similar provided that the correct amount of fertilizer nitrogen was given. On Hoosfield three different cultivars of spring barley have been grown since 1970 and on both soils the same four amounts of nitrogen fertilizer tested.

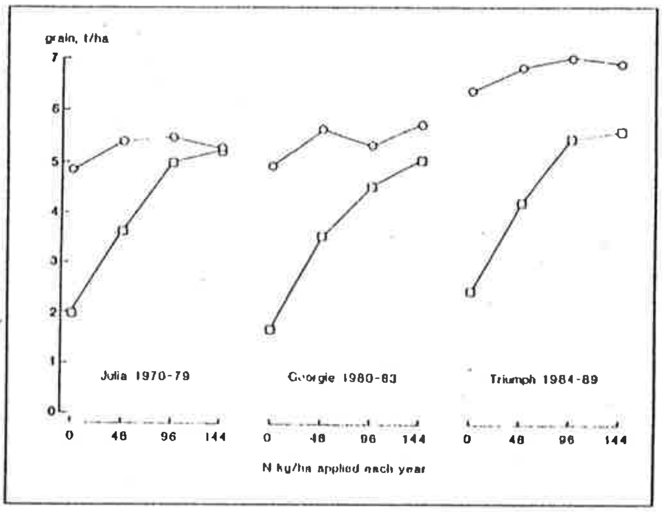


Figure 6: Yields of three cultivars of spring barley given four amounts of nitrogen and grown on soils receiving only fertilizers (□) or farmyard manure (○) since 1852. Hoosfield Continuous Barley Experiment, Rothamsted. [Johnston, 1991 a]

Figure 6 (taken from [Johnston, 1991 a]) shows that yields of cultivar (cv) Julia, 1970–79 were the same on both soils with optimum nitrogen. But then yields first of cv Georgie, 1980–83, and then Triumph, 1984–89, have been larger on soils with more organic matter. This is not because soil humus has decreased on fertilizer treated soils, it has been the same throughout (Figure 4). The reason is that current cultivars have a high yield potential and the judicious use of the wide range of agrochemicals currently available will protect that potential. To achieve the best yields requires attention to the physical properties of soil which govern root development and soil humus is an important contributory factor to these properties.

8 Environmental studies

There is currently much concern that intensively managed husbandry systems are putting soil fertility at risk. But equally there are risks to agriculture from mans' anthropogenic activities. Selected samples of the archived crops and soils taken since the start of the Broadbalk experiment have recently been analysed for their content of both cadmium [Jones et al., 1987] and polynuclear aromatic hydrocarbons (PAHs) [Jones et al., 1989].

Figure 7 shows changes in the soil burden of cadmium, (Figure 7a) and PAHs (Figure 7b) in the top 23 cm of the unmanured plot. The amount of both pollutants has increased appreciably, since the 1940s for cadmium and 1950s for PAHs. Figure 7a also shows that the measured changes in soil cadmium compared well with predicted increases based on assumptions about temporal trends in atmospheric cadmium additions. On plots treated with superphosphate there was little additional increase in the cadmium content [Jones et al., 1987]. The increase in PAH content probably arises from increases in low temperature combustion of organic compounds. It is only with such data, derived from archived soils taken from plots with a well- documented history as in long-term experiments, that background levels of such pollutants can be defined. Without such data it would be difficult to ascribe much of the present pollutant burden to mans' anthropogenic activities over the last 40 to 50 years.

Analysis of archived grain samples indicated that little of either of these pollutants are found in the grain and there has been little change with time [Jones & Johnston, 1989, Jones et al., 1989]. However, similar data were also obtained for the herbage samples from the Park Grass experiment, started in 1856. This experimental site has been in undisturbed grassland for at least 300 years. The concentrations of both cadmium and PAHs are much larger than in the grain samples. In part, this could be atmospheric deposition on the surface of the vegetation but wherever

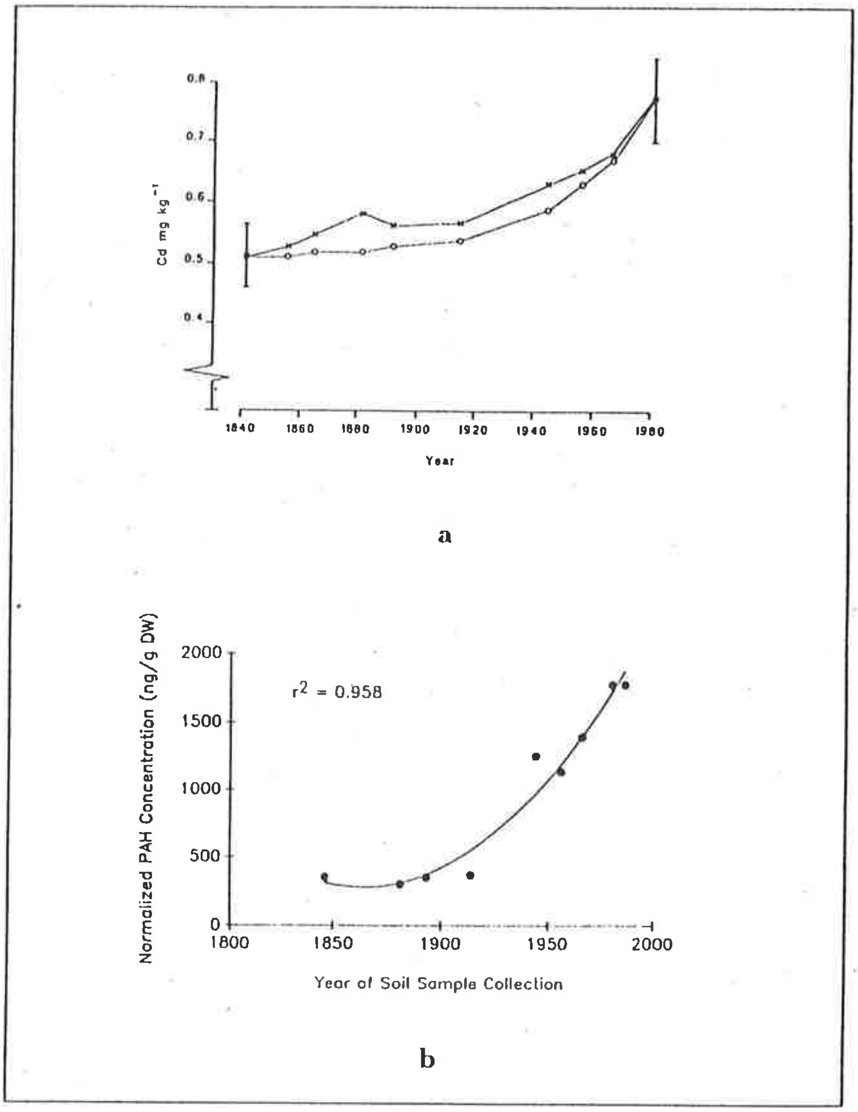


Figure 7: Changes with time in the concentration of cadmium (Fig. 7a) and polynuclear aromatic hadrocarbon (PAHs) (Fig. 7b) found in the plough layer of the unmanured soil on Broadbalk at Rothamsted. [Jones et al., 1989]

located, these pollutants will be ingested by grazing herbivores. A very interesting set of data only recently acquired shows the changing levels of lead in herbage [Jones et al., 1990]. Again the lead could be a surface contaminant or within the tissue but in either location it will be ingested by herbivores. Figure 8 shows that although the concentration of lead has fluctuated there is a marked downward trend in the 30-year period since 1957. This reflects the declining use of lead tetraethyl as an additive to petrol, probably the largest source of aerial lead. Further reductions

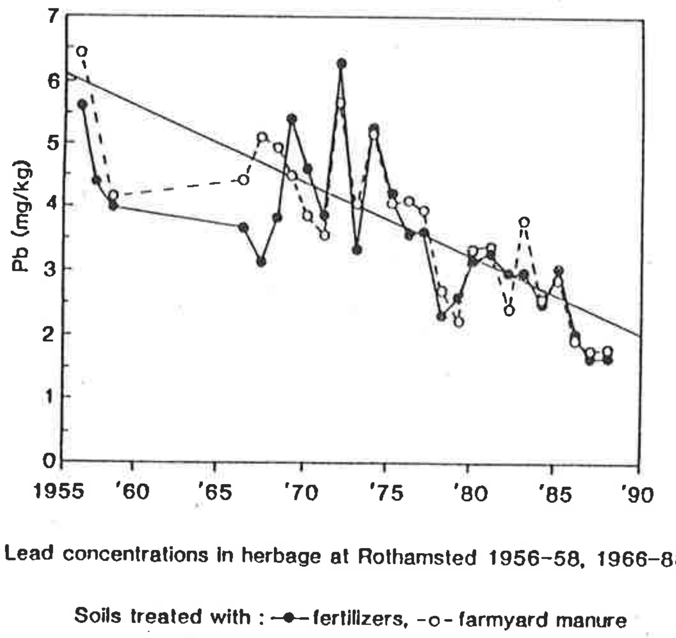


Figure 8: Change with time in the concentration of lead measured in unwashed herbage samples from the Rothamsted Reference experiment. [Jones et al., 1990]

in permitted levels of lead in petrol and the introduction of lead-free petrol in 1985 appears to be associated with the very sharp decline in lead concentrations in the herbage since 1986.

An important feature of the date in Figure 8 is that from 1978 to 1985 the concentration of lead appeared to increase. An eight-year period of monitoring is often considered to be more than adequate to detect change but the data for this eight-year period could have been used to draw totally incorrect conclusions. It is only over the longer time scale that the underlying downward trend becomes obvious.

9 Conclusions

Without doubt Lawes & Gilbert made an invaluable contribution to agricultural science and to the well being of countless generations of people by showing how food supplies could be insured and increased by supplementing the supply of plant nutrients available in soil. Liebig's view that it was unnecessary to supply additional, readily available supplies of nitrogen to get acceptable yields of agricultural crops was clearly wrong as were other aspects of his Mineral Theory. In relation to this part of his contribution to scientific knowledge perhaps one of the more charitable quotes is, *„...though so brilliant a chemist (Liebig) lacked biological training and, as I have always felt, a biologist's instincts“* [Hopkins, 1936].

Lawes & Gilbert left a legacy of long-term experiments which today are an invaluable resource. In more quizzical moments I occasionally wonder whether Lawes & Gilbert would have continued with some of their experiments beyond the stage of all reasonable doubt about the results if it hadn't been for the intransigent views of Liebig which he expressed in such a vitriolic way over a period of twenty years or so. However, Lawes & Gilbert did continue and it says much for those who followed them that their experiments have never become fossilized monuments to the past achievements of their founders. Today data from the Rothamsted experiments have value to agriculture, they have added value in complementary studies on environmental problems.

Any worthwhile future for the generations yet to come will depend on a better understanding between how to feed people whilst maintaining an acceptable environment for them to live in. Much therefore depends on the ability of current research to first model processes and then predict change. The ability to do this well depends on results from well-founded long-term experiments. It is essential that this message is carried to the politicians of today who must fund such experiments for the benefit of future generations.

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