Des experimentations de longue durée sur la recherche en environnement.

Un exemple pris en Grande Bretagne

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RÉSUMÉ

Rothamsted possède des séries d'expérimentations de longue durée, la plus ancienne ayant débuté en 1843. Ces expérimentations ont été utilisées en particulier pour suivre la qualité des sols en relation avec son utilisation ou d'autres pressions. La recherche a montré comment le carbone peut augmenter rapidement lors du passage d'une terre cultivée à une prairie ou au développement d'une occupation forestière, ou lorsque des fumiers d'origine animale sont apportés régulièrement. A l'inverse, une terre arable perd son carbone même lors de rotations avec de la prairie. Les résultats de ces expériences ont été utilisés pour aider à la mise au point des modèles internationalement connus que sont ROTH-C (sur le cycle du carbone) et SUNDIAL (cycle de l'azote). Les flux de nitrate et phosphate vers l'eau, et ceux du méthane des oxydes d'azote et de l'ammonium vers l'atmosphère ont été mesurés et mis en relation avec les pratiques de gestion des terres. Rothamsted a les plus longues séries de données sur les pluies acides du monde. Cela a été exploité avec les échantillons de sol et de végétation des expériences de longue durée, pour mettre en évidence les dépôts acides et leurs effets sur le sol et la végétation. Les analyses d'échantillons de sols et de plantes montrent l'accumulation ou au contraire la décroissance de la pollution par les métaux lourds ou polluants organiques tels que les dioxines, les furanes ou les PCBs. Les impacts de tels polluants sur les microorganismes ont été étudiés. Les expérimentations de Rothamsted vont continuer à fournir des renseignements uniques sur la qualité des sols, l'impact de l'agriculture sur l'environnement et la durabilité de l'agriculture.

Mots clés

Qualité des sols, pollution, métaux lourds, polluants organiques persistants, dépositions acides, cycle du carbone et de l,azote, émissions de gaz.

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SUMMARY

LONG-TERM EXPERIMENTS IN ENVIRONMENTAL RESEARCH : an example from the UK

Rothamsted has a series of long-term experiments, the first of which was started in 1843. These experiments have been used to assess changes in soil quality, amongst other things, as affected by management and other controlling factors. Research shows how carbon in soil increases rapidly under arable land newly sown to grass or left for woodland to regenerate, and when animal manures are applied regularly to arable land. Conversely, arable land loses soil carbon even in rotations with grass. Data from the experiments have been used to help create the internationally accredited models ROTH-C (carbon cycling) and SUNDIAL (nitrogen cycling). Fluxes of nitrate and phosphate to waters and methane, nitric oxide, nitrogen dioxide and ammonia have also been measured and related to land management practices. Rothamsted has the longest set of acid rain data in the world. This has been used with plant and soil samples from the long-term experiments to assess acid deposition and its impacts on soils and vegetation. Analysis of soil and plant samples from the experiments show the build up and depletion of heavy metal and organic pollutants such as dioxins, furans and PCBs. The impacts of such pollutants on soil microorganisms has been studied. The long-term experiments at Rothamsted will continue to provide a unique resource that allows soil quality, the impact of agriculture on the environment and the sustainability of agricultural systems to be assessed.

Key-words

Soil quality, pollution, heavy metals, organic pollutents, acid deposition, carbon and nitrogen cycling, gaz emission.

RESUMEN

EXPERIMENTACIONES DE LARGAS DURACIÓN SOBRE LA INVESTIGACIÓN EN MEDIO AMBIENTE :
un ejemplo en Gran Bretaña

Rothamsted tiene series de experimentaciones de largas duración, la más vieja empezó en 1843. estas experimentaciones fueron usadas en particular para seguir la calidad de los suelos en relación con su uso o otros presiones. La investigación muestra como el carbono puede aumentar rápidamente cuando se pasa de una tierra cultivada a une pradera o al desarrollo de una ocupación forestal, o cuando abonos de origen animal son aportados regularmente. Al contrario una tierra arable pierde su carbono mismo durante rotaciones con pradera. Los resultados de estas experiencias fueron usados para ayudar a validar modelos internacionalmente conocidos que son ROTH-C (sobre el ciclo del carbono) y SUNDIAL (ciclo del nitrógeno). Los flujos de nitratos y fosfatos hacia el agua, y los del metano, de los óxidos de nitrógeno y del armonio hacia la atmósfera fueron medidos y relacionados con practicas de gestión de tierras. Rothamsted tiene las más largas series de datos sobre las lluvias ácidas del mundo. Esto fue usado con las muestras de suelos y de plantas de los experimentos de largas duración, para poner en evidencia los depósitos ácidos y su efecto sobre el suelo y la vegetación. Los análisis de muestras de suelos y de plantas muestran la acumulación o al contrario la baja de la polución por los metales pesados o contaminantes orgánicos tales dióxinas, furanes o PCBs. Los impactos de estos contaminantes sobre los microorganismos fueron estudiados. Las experimentaciones de Rothamsted siguen proviniendo informaciones únicos sobre la calidad de los suelos, el impacto de la agricultura sobre el medio ambiente y la sostenibilidad de la agricultura.

Palabras clave

Calidad de los suelos, contaminación, metales pesados, contaminantes orgánicos persistentes, deposiciones ácidas, ciclo del carbono y del nitrógeno, emisión de gas.

Many scientists have sought to define and assess soil quality or fertility and the many factors that can influence it (e.g. Doran and Parkin, 1994). As yet, however, there is no internationally agreed system for measuring soil quality and only a few national systems in use; most of these are focused on agricultural soils (e.g. Schipper and Sparling, 2000). The need for monitoring changes in soil quality is recognised within programs such as the Long-Term Ecological Research (LTER) in the USA and the Environmental Change Network (ECN) in the UK where many important soil properties are measured (Risser, 1991). However, such programs take time to establish and it may be many years before useful information on long-term changes becomes available from them.

The importance of existing long-term experiments should not be underestimated in making useful current assessments of soil quality and for monitoring change. There are a large number of these experiments around the world; many are listed by Smith *et al.* (2002). They provide the best practical means of studying the effects on crop growth and soil properties of factors such as soil acidification or declining levels of organic matter. These factors may, in turn, be affected by others such as global change or inappropriate management. These effects and any interactions between factors may take decades to become apparent. Thus long-term experiments increase in value with age.

Implicit in any statement about the value of long-term experiments is the fact that they must be well managed, that any changes have been carefully considered and that they are well documented. Leigh *et al.* (1994) give examples of how this can be achieved.

Most managers of long-term experiments now accept that they need to be as relevant to modern agriculture and environmental concerns as possible, and that often means adaptation. If the experiments are not relevant then it becomes more difficult to justify the cost of maintaining them. However, any modifications should not compromise the long-term integrity and continuity of the experiment. Changes should not be made to address essentially short-term issues that could easily be answered elsewhere.

THE ROTHAMSTED 'CLASSICAL' AND OTHER LONG-TERM EXPERIMENTS

Rothamsted has a series of long-term experiments, the first of which was started in 1843. A partial list is given in *table 1.* The most important of these for environmental research are Broadbalk Winter Wheat, now in its 160th year, Park Grass (permanent grass cut for hay, almost 150 years old), Broadbalk and Geescroft Wildernesses (arable land left to revert to woodland by natural regeneration 120 years ago) and Knott Wood (deciduous woodland at least 300 years old). The history and some of the many applications of these experiments to agricultural and environmental research were reviewed on the 150th anniversary of their beginning (Leigh & Johnston, 1994) and more recently in the context of other long-term experiments around the world (Rasmussen *et al.,* 1998).

The experiments are very carefully controlled through a committee that oversees maintenance, sampling and storage of samples, and any changes to the experiments. Some changes have been made to make the experiments more relevant to current needs and problems but without compromising the integrity of the experiments. Both soil and plant samples are taken regularly, plant samples every year, and carefully dried and stored in an archive that now contains very 250,000 samples. These can be used with current samples to assess changes with management, climate and other controlling factors.

The experiments have been used to study many environmental problems, most of which could not have been anticipated when the experiments began. It is to the great credit of John Lawes and Joseph Gilbert who began many of them, and can be seen as the founders of long-term experiments and long-term research, that the experiments were so well planned and remain relevant after almost 160 years. Some examples of the uses to which they have been put in recent years are given below.

NUTRIENT CYCLING AND MODELLING

The long-term experiments have been some of the most important experimental sites in the world for studying nutrient cycling, including carbon. Examples given here focus on the construction of carbon and nitrogen cycling models and measurements of losses of nutrients to the environment but there have been many other applications such as the build up and depletion of reserves of nutrients in soils and critical nutrient levels.

Soil organic matter (SOM) has always been a focus of attention in the context of the physical, chemical and biological properties of soils. However, it has now become one of the main indicators of soil quality, with research moving from measurements of total SOM or organic carbon (OC) to SOM fractions (Sohi *et al.,* 2001). Data from the long-term experiments has been fundamental in constructing, and validating, the Rothamsted Carbon Model (RothC) which simulates the turnover of SOM (Jenkinson 1990). Part of the validation involved the analysis of archived crop and soil samples for ^{14}C to see whether the model would accurately simulate the input of labelled C into soil as a result of the atmospheric thermonuclear tests of the 1960s (Jenkinson *et al.,* 1992). In a unique collaborative experiment, data from the long-term experiments was used to test 8 carbon cycling models (Smith *et al.,* 1997).

Soil organic matter will tend towards an equilibrium value which depends on the management system being practised, the amount of organic material added and its rate of decomposition, the rate of breakdown of existing organic matter, soil texture and climate. Most soils will not be in equilibrium but will be increasing or decreasing, depending on all these factors. The long-term experiments show how carbon in soil increases rapidly under arable land newly sown to grass or left for woodland to regenerate, and when animal manures are

Tableau 1 - Les expérimentations de longues durée à Rothamsted (les expérimentations classiques et les autres)
Table 1 - *The 'Classical' and other long-term experiments at Rothamsted, as of 2002. (The list is not exhaustive)*

Experiment	Start date	End date	Applications
Broadbalk Winter Wheat	1843		Sustainability of wheat yields ; nutrient losses from arable land ; pest and disease control in cereals.
Broadbalk Wilderness	1882		Natural regeneration of woodland from abandoned arable land ; atmospheric deposition ; soil acidification ; carbon and nitrogen cycling.
Geescroft Wilderness	1885		ditto
Knott Wood (At least 300-year old woodland)	1700?		Atmospheric deposition ; soil acidification ; nitrogen cycling.
Hoosfield Alternate Wheat and Fallow	1856		Fallowing
Hoosfield Spring Barley	1852		Factors controlling barley growth ; nutrient losses from arable land ; carbon cycling ; sustainability of cereal yields.
Exhaustion Land	1856		Nutrient depletion and build up in soils ; impacts of soil acidity.
Park Grass	1856		Impacts of nutrients and atmospheric deposition on biodiversity of grassland ; soil acidification.
Barnfield	1843		Nutrition of root crops ; importance of organic manures ; long-term effects of nutrient residues.
Agdell	1848	1990	Nutritional requirements of crop rotations ; diseases of root crops ; importance of soil reserves of P and K.
Garden Clover	1854		Agronomy of clover production.
Rothamsted And			
Woburn Ley-Arable	1849 & 1938		Carbon build up and depletion under various ley-arable rotations.
Woburn Organic Manuring	1963		Importance of various organic manures ; impacts of organic amendments on soil carbon.
Woburn Market garden	1842		Impact of sewage sludge and other organic manures in crops ; accumulation of heavy metals from sewage sludge ; impacts of metals on soil quality.
Long-term Liming	1961		Impacts of lime on soil pH ; lime requirements.
Saxmundham Rotations	1899		Crop nutrition on heavy soils ; critical nutrient levels ; reserves of P and K in soils.

Figure 1 - Effet des passages prairie-culture (avec labour) ou sol cultivé- prairie sur la teneur des sols en carbone (expérimentations de Rothamsted prairie-cultures)
Figure 1 - *Effect on soil carbon content of ploughing out grass, or of sowing grass on arable land. Data from the Rothamsted Ley-arable experiments*

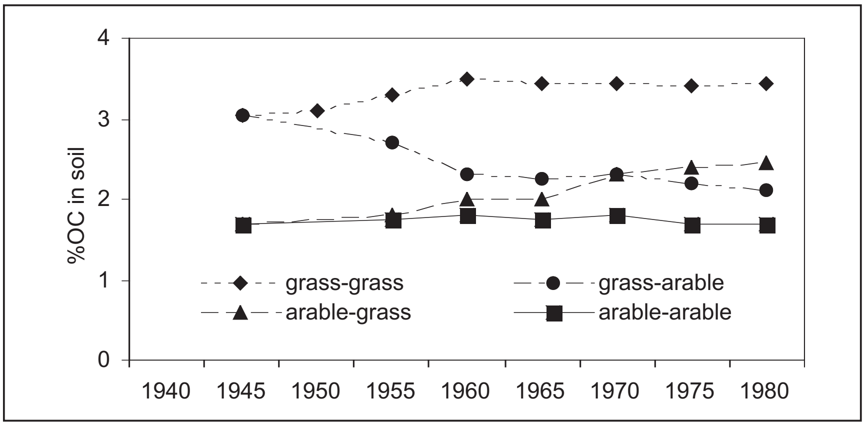
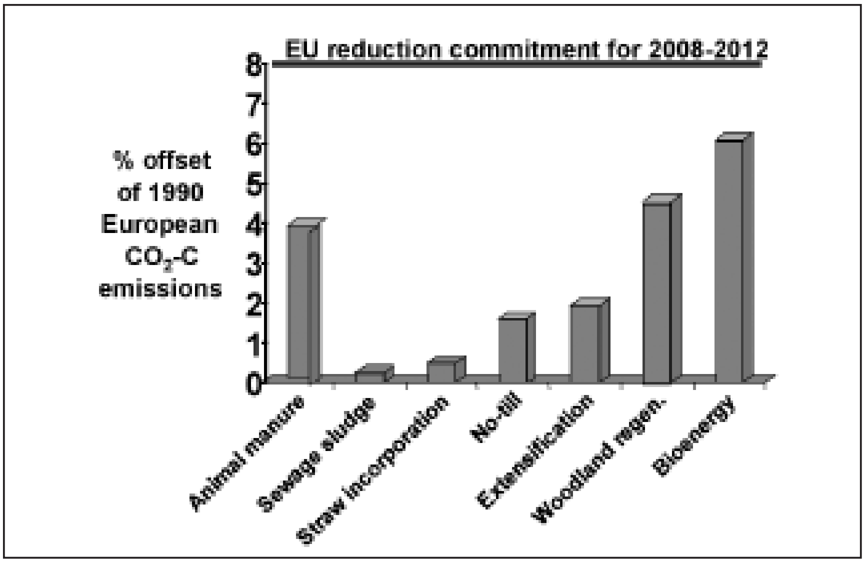


Figure 2 - Différentes options de compensation des émissions par le carbone prédit à partir des changements de teneurs des expérimentations de longue durée de Rothamsted, incluant les émissions de N_20 et CH_4

Figure 2 - *Carbon mitigation options predicted from soil carbon changes in some of the long-term experiments at Rothamsted, including the impacts on N_2O and CH_4 fluxes (Smith et al., 2001)*



applied regularly to arable land. Conversely, arable land loses soil carbon even in rotations with grass *(figure 1)*.

New experiments are studying the impact of biomass fuel crops such as Miscanthus on carbon cycling and mitigation strategies for reducing CO_2 emissions. New plots growing maize have been established on some long-term experiments to facilitate ^{13}C tracer studies and soil organic matter turnover research, a subject of great interest in many countries (Balesdent *et al.,* 1987 ; Agren *et al.,* 1996 ; Bird *et al.,* 2003). Relationships between management and carbon content have been used to assess options for sequestering carbon into soils and mitigating CO_2 emissions, including the impact on the other greenhouse gases N_2O and CH_4 (*figure 2* and Smith *et al.,* 2001).

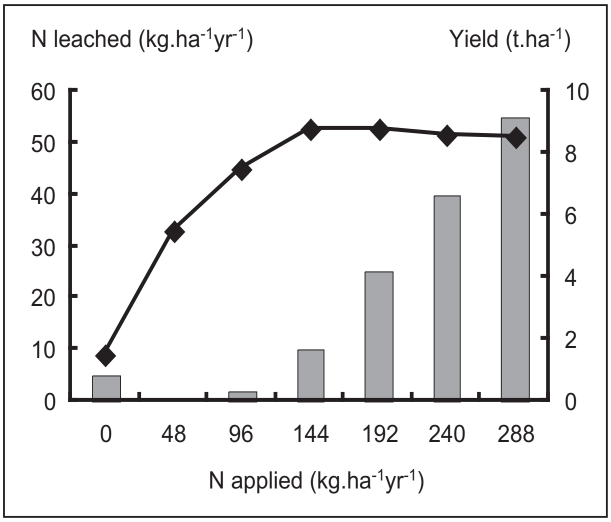
NUTRIENT LOSSES FROM AGRICULTURAL LAND TO AIR AND WATER

Data from the experiments have also been used to help create the SUNDIAL nitrogen cycling model (Smith *et al.,* 1996) and are currently being used to develop a phosphorus loss model, PSALM (Addiscott *et al.,* 2002). Such models are vital tools for testing hypotheses and revealing gaps in our understanding and for exploring future scenarios.

The Broadbalk Experiment had land drains inserted in 1849. These were opened up for sampling in 1868. The observation by Thomas Way that, although potassium, sodium and magnesium were applied as fertilisers to Broadbalk, mostly calcium was leached in the drainage waters led to the development of the theory of cation exchange (Way, 1850). Samples collected from the drains over time allow the concentrations and amounts of nitrate and phosphate leached to waters to be measured. The data show that nitrate leaching is small until more fertiliser is applied than the crop can use ; it then increases rapidly (Goulding *et al.,* 2000 and *figure 3*). Phosphate losses by leaching have been observed to be small but to increase significantly when the soil P content (measured by Olsen's method) exceeds a critical value (Heckrath *et al.,* 1995). Recent research has tried to discover the mechanisms controlling this (McDowell *et al.,* 2002).

Figure 3 - Réponses des récoltes à l'azote et pertes correspondantes par lixiviation (expérimentation sur premier blé à Broadbalk)

Figure 3 - *Crop response to nitrogen and corresponding leaching losses from a 1st wheat on the Broadbalk Experiment*



Losses of nitrous oxide by denitrification have been measured on all the long-term experiments. These show emissions increasing with nitrogen fertiliser application above the optimum for the crop, as for nitrate leaching. They also show that emissions of nitrous oxide from the woodland are as large or larger than those from the arable land because of the very large amounts of nitrogen deposited to the trees from the atmosphere (Goulding *et al.,* 1998).

Fluxes of methane, nitric oxide, nitrogen dioxide and ammonia have also been measured and related to land management practices. Methane oxidation by aerobic soils is greatly decreased by cultivation and further decreased by applying nitrogen fertilisers and organic manures (Goulding *et al.,* 1995).

ACID RAIN AND SOIL ACIDIFICATION

Rain has been collected and analysed at Rothamsted since 1853. Gases and particles have been analysed since 1986. Rothamsted has the longest set of acid rain data in the world *(figure 4).* This has been used with plant and soil samples from the long-term experiments to assess acid deposition and its impacts on soils and vegetation (Blake *et al.,* 1999). The results show clearly that acid rain is the largest source of acidity, larger than that from soil organic matter decomposition and plant uptake.

Archive samples have been combined with new samples from the long-term experiments to study soil acidification *(figure 5).* This is a world-wide problem that can have a major effect on sustainable land use, both through the direct influence on yield and through the mobilisation of heavy metals. The Park Grass experiment was started in 1856 on a site thought to have been in grass for several hundred years. Two plots have remained unmanured since then. Initially the 0-23 cm depth of soil had a pH (in H_2O) of c. 5.6. Less than 1 km away on the same soil type) is the Geescroft Wilderness. This was part of an arable experiment until it was fenced off in 1885 at which time the pH was c. 7.1. Since then the site has been left untended and a mature deciduous woodland has developed. Acidification, arising at least in part from aerial pollution, has been quicker and more intense (about 3 pH units in 100 years in the top 23 cm on Geescroft) than on Park Grass (about 1 pH unit in 140 years). The difference between the two sites is caused by the tree canopy being more efficient at trapping aerial pollutants than the low growing grassland. Under the trees the subsoils have also acidified appreciably down to 1 m. On both sites aluminium has been mobilised with toxic heavy metals. The developing acidity has and reduced the diversity of plant species in the grassland, both in terms of numbers of species and their distribution (Tilman *et al.,* 1994). In contrast, Broadbalk Wilderness has not acidified because it was

Figure 4 - Apports par les précipitations à Rothamsted (1853-2000)
Figure 4 - *Deposition in precipitation at Rothamsted (1853-2000)*

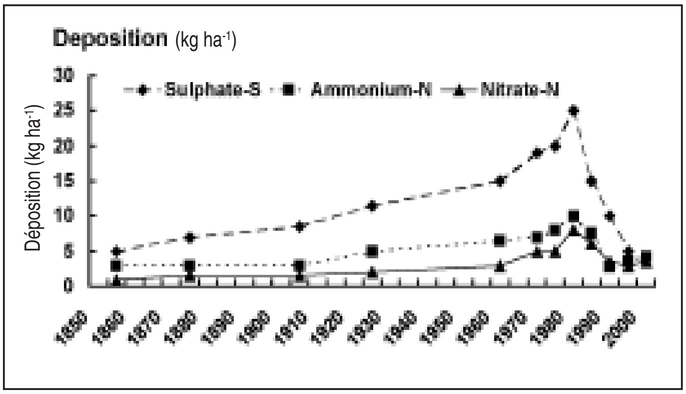


Figure 5 - Acidification du sol pour quelques expérimentations de Rothamsted
Figure 5 - *Soil acidification under some of the long-term experiments at Rothamsted*

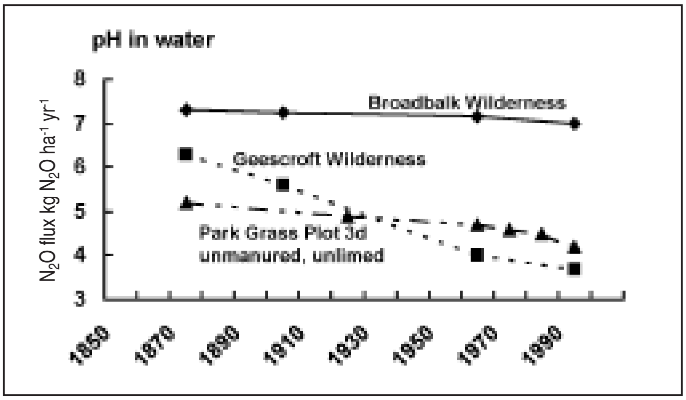
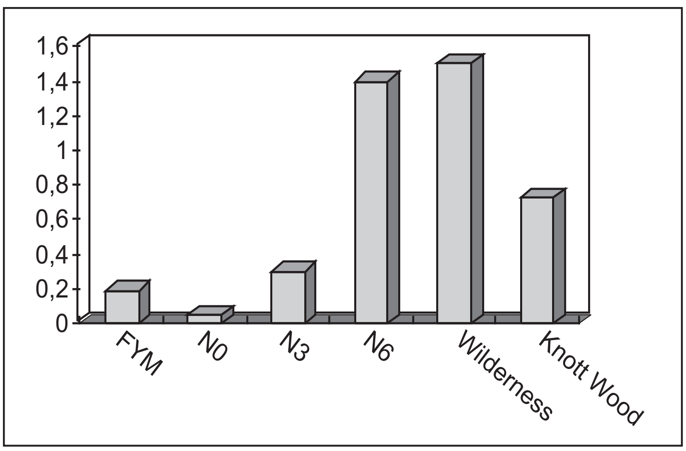


Figure 6 - Flux annuels d'oxyde nitreux (N_20) à partir des expérimentations de Brodbalk, Broadbalk wilderness et Knott wood
Figure 6 - *Annual nitrous oxide fluxes from plots of the Broadbalk Winter Wheat Experiment, Broadbalk Wilderness and Knott Wood*



'limed' with large amounts (250 t ha^{-1}) calcium carbonate in the early 19th century.

ATMOSPHERIC DEPOSITION

Acid rain is a particular form of atmospheric deposition. Recently attention has moved from acid rain towards nitrogen deposition. Deposited nitrogen contributes to acid rain in some of its forms, notably ammonia and ammonium. Also inputs of ammonia from livestock and oxides of nitrogen (NOx) from combustion to some ecosystems exceed the 'Critical Load' of nitrogen that can be utilised by those ecosystems ; they become 'Nitrogen Saturated' (Vitousek *et al.,* 1997). The long-term experiments at Rothamsted have been invaluable for calculating amounts of nitrogen deposited to arable land, grassland and woodland from the atmosphere. Calculations have arrived at the very large amount of 43 kg N ha^{-1} yr^{-1} deposited to arable land at Rothamsted (Goulding, 1990 ; Goulding *et al.,* 1998a,b). We have evidence that woodland at Rothamsted receives nitrogen inputs above the Critical Load. The larger surface area of deciduous tress scavenges gaseous and aerosol forms of nitrogen more effectively than arable crops ; up to 200 kg N ha^{-1} yr^{-1} may be deposited to the small area of Broadbalk Wilderness with its very large edge effect. We have measured nitrous oxide emission rates from all plots of the Broadbalk Winter Wheat experiment, including of 1.5 kg N_2O ha^{-1} yr^{-1} from Broadbalk Wilderness *(figure 6)*. This is more than the amount (1.4 kg N_2O ha^{-1} yr^{-1}) emitted from the nearby plot on the Broadbalk Winter Wheat Experiment receiving 288 kg N ha^{-1} yr^{-1}, but is in proportion to the excess nitrogen entering each ecosystem (Goulding *et al.,* 1998a).

The measured amount deposited at Rothamsted does not agree with national estimates of nitrogen deposition of 20-25 kg N ha^{-1} yr^{-1} for the Rothamsted area (NEGTAP, 2001). It is not easy to reconcile the two estimates. Those made at Rothamsted include all forms of nitrogen, including nitric acid aerosol, and are adapted for changes in crop cover through the year. It is possible that the deposition velocities used to convert measured concentrations to estimates of amounts deposited may be too large for Rothamsted. However, we have three alternative estimates of deposition at Rothamsted. Very old lysimeters (the «Drain gauges», Addiscott, 1988) and short- and long-term nitrogen N balances on Broadbalk all suggest between 35 and 50 kg N ha^{-1} are deposited each year *(table 2)*. It is possible that the NEGTAP estimates based on 5 km grid squares cannot adequately reflect deposition at a single site.

METAL AND ORGANIC POLLUTANTS

Analysis of soil and plant samples from the long-term experiments show the build up and depletion of pollutants in soils and crops and enable the sources of pollutants to be identified (e.g. Jones *et al.,* 1994). The increases over time in the amounts of dioxins, furans and PCBs can be measured in the soils, and a decline in PCBs can be measured from the time their use was prohibited *(figure 7)*.

The impacts of pollutants on soil microorganisms has been studied, focusing on toxic heavy metals from sewage sludge (e.g. Brookes & McGrath, 1984) ; the fixation of nitrogen by rhizobia is inhibited by some toxic metals (Hirsch *et al.,* 1993). New research is examining the impacts of organic pollutants. Pesticides seem to have little long-term impact on the soil quality (Lin & Brookes, 1999).

THE UK ENVIRONMENTAL CHANGE NETWORK (ECN)

The ECN establishes and maintains a selected network of sites within the UK from which to obtain long-term datasets through the monitoring of a range of variables identified as being of major environmental importance. From these it looks for evidence of natural and man-induced environmental changes and improve understanding of the causes of change. The ECN is linked to other national networks, such as those in Europe, the USA and China, and has a website at : http://www.ecn.ac.uk/links.htm.

The whole of the farm at Rothamsted is part of the ECN, although most measurements focus on the long-term experiments and especially Park Grass, as this is of most interest. Having been established in 1992 the ECN is now 10 years old and, with the very long-term data from Rothamsted now has an invaluable database for assessing soil quality amongst many other environmental concerns. Its value will grow with age.

SOIL BIODIVERSITY AND FUNCTION

The long-term experiments are beginning to be used to study the impacts of management on soil biodiversity and its interaction with soil function. Methods such as BIOLOG® and Substrate Induced Respiration attempt to measure the functional microbial diversity of soils. Data suggest that management practices such as cultivation cause large changes in the functional diversity of soil microorganisms (O'Flaherty *et al.,*

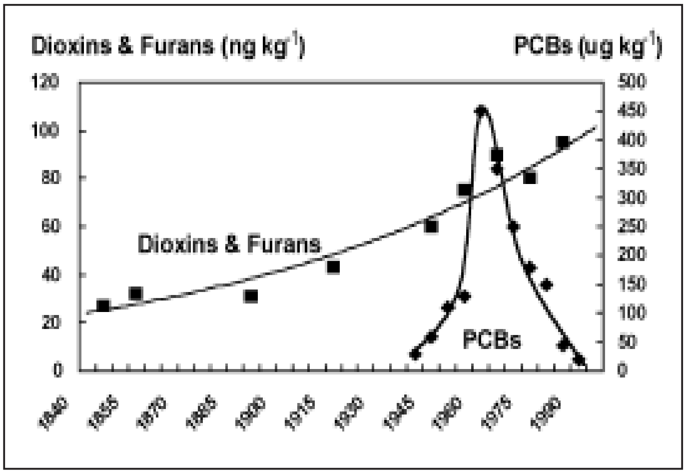
Tableau 2 - Estimation des dépots d,azote sur terres cultivées à Rothamsted en 1986 (kg $ha^{-1}an^{-1}$)

Table 2 - *Estimates of nitrogen deposition to arable land at Rothamsted in 1996 (kg N ha^{-1} yr^{-1})*

Direct measurement	«Drain Gauges»	Long-term N balance on Broadbalk	$_{15}$N balance on Broadbalk
43.3	37	38	48

Figure 7 - Comportement des polluants persistants dans les sols (expérimentations de longue durée de Rothamsted)

Figure 7 - *Pollutants in soils from long-term experiments at Rothamsted*



2001). There is much criticism of these new methods, however, and further research is needed to test them. Long-term experiments are excellent sites for such research.

CONCLUSIONS

The long-term experiments at Rothamsted and elsewhere will continue to provide a unique resource that allows the long-term impact of agriculture on the environment and the sustainability of agricultural systems to be assessed. It is impossible to predict all new future applications. However, some research of immediate importance can be suggested that will help funders and other users to appreciate the value of these experiments and support them :

1. The long-term fate of organic matter (animal manures, human waste, composts) applied to land.
2. Equilibrium and optimum soil organic matter contents under different land managements for soil quality.
3. The role of soil biodiversity in maintaining biogeochemical function for sustainable development.

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