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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: WT03051

2. Project title: Review of Research on Recycling of Sewage Sludge to Agricultural Land

3. Contractor organisation(s): ADAS

4. Total Defra project costs: £ 29,786

5. Project: start date..... 01/02/2006

   end date..... 31/04/2006

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so.....**YES** ✓ **NO** ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.
Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.
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(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

The objective of this study was to collate and summarise all research and development work on the recycling of sewage sludge to agricultural land (defined as land used to grow crops for food and animal feed) from 1998 to the present day. The review primarily considered research funded by Defra (previously DETR and MAFF), but has set this in the context of UK work from other funders (e.g. UKWIR, EA) and internationally (e.g. EU) funded studies. Projects funded in other areas such as livestock manures, composting and 'waste' were also included where the findings were considered to have important implications for sewage sludge recycling to agricultural land.

The study grouped the research and development projects into the following major topic areas, viz:

- Literature reviews and desk studies
- Sludge use on agricultural land
- Heavy metals
- Organic contaminants
- Pathogens
- Radionuclides
- Nutrient losses to the environment
- Fertiliser value of sludge
- Soil quality

For each topic, the key findings of each project were summarised to produce a concise overview of the current state of knowledge in that area. Detailed project summaries were provided in an Appendix to the main report.

In short, it was found that since 1998, there have been more than 60 projects commissioned in England and Wales involved with sewage sludge recycling to agricultural land. Research funded by Defra, MAFF, DETR and the FSA has covered important topics such as the effects of sludge heavy metals on long-term soil fertility, the fate and behaviour of organic contaminants in sewage sludge, and pathogen losses to the water environment. UK Water Industry Research (UKWIR), which facilitates collaborative research for water operators, has led or contributed to many of these projects on the potential environmental and health impacts of sludge recycling to agriculture, as well as to research on the agronomic and soil quality benefits of sludge recyling to agricultural land. Other notable funders of UK research include the Environment Agency, EPSRC, SEERAD, WAG and SEPA, along with individual Water Operators. In general, the number of jointly funded projects was indicative of good communication between the funding

organisations and has minimised the potential duplication of research effort.

Based on this review of recent past and ongoing research on sludge recycling to land, broad subject areas were identified where more research or information was needed. The recommendations included :

1. Up-to-date information on the quantities, types and quality of sludge products being applied to agricultural land should be collected.

2. The 'Heavy Metal Inventory' should be updated at regular intervals to reflect changes in farming practices, 'waste' (especially sludge and compost) production and re-use practices, and the regulatory environment.

3. There is a pressing need to continue the "Long-term Sludge Experiments" to provide robust scientific information to ensure that heavy metal additions in sludge (and other organic materials) do not compromise soil microbial activity and long-term fertility. These sites also provides an experimental base to evaluate the impact of Cd additions to soils on cereal grain quality to ensure that grain Cd concentrations do not exceed specified EU legal limits.

4. More robust measurements of ammonia and nitrous oxide emissions following land spreading and during sludge treatment prior to land spreading are required.

5. More research is needed on the agronomic benefits of enhanced treated sludge products at the field scale, together with a requirement to quantify the medium/long term effects of sludge products on soil quality, and to assess the long-term water quality impacts of sludge recycling to agricultural land.

6. Holistically, there is a need to consider how to minimise contaminant levels at source to improve the quality of sludges and thereby sustain the agricultural recycling route.

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

1. Introduction and background

1.1 Objective

The objective of this report was to collate and summarise all research and development work on the recycling of sewage sludge to agricultural land (defined as land used to grow crops for food and animal feed) from 1998 to the present day. The review primarily considered research funded by Defra (previously DETR and MAFF), but has set this in the context of UK work from other funders (e.g. UKWIR, EA) and internationally (e.g. EU) funded studies.

1.2 The legislative framework

Current controls on the recycling of sewage sludge to agricultural land are based on the 1986 EU Sludge Directive (86/278/EEC) which was implemented in Britain in 1989 through the Sludge (Use in Agriculture) Regulations. The regulations are supported by a Code of Practice (DoE, 1996) which embodies best practice guidelines on sludge recycling to land, including maximum permitted soil heavy metal concentrations and sludge application rates. Revisions to the Sludge Directive are expected, and a third draft of a 'Working Document on Sludge' (ENV.E.3/LM April 2000) was produced by the EC for consultation. The suggested amendments are likely to reduce the maximum permitted heavy metal limits in soils to which sludge can be applied, introduce microbiological limits for the final sludge product, formalise the record keeping and introduce hazard analysis and critical control point (HACCP) procedures to ensure improved quality control. The current status is that work on revision of the Directive is likely to resume again in 2007.

In addition to the legislation, a voluntary agreement, the "Safe Sludge Matrix", has been in place throughout the UK since 1999 (ADAS, 2001). The agreement, brokered by ADAS, between Water UK representing the UK Water and Sewerage Operators and the British Retail Consortium (BRC) has had an important influence on the on-going revision of the EU Sludge Directive. The "Safe Sludge Matrix" included inputs from the Environment Agency, Defra and the Food Standards Agency (FSA), with extensive consultation with other stakeholders such as the National Farmers Union (NFU), Country Land and Business Association (CLA), food manufacturers and food processors. The Matrix requires strict controls on the microbiological quality of sludge and that no harvest/grazing intervals are adopted following application to agricultural land used to grow food crops. In addition, the use of untreated sludge on land

growing food crops was phased out at the end of December 1999 and on all agricultural land at the end of December 2005. The Matrix provides robust safeguards for all stakeholders – farmers, food retailers, food processors and consumers

2. Literature reviews and desk studies

2.1 UK studies

In 1998, DETR funded a review of the scientific evidence relating to controls on the agricultural use of sewage sludge (Carrington *et al*., 1998). This was divided in two parts, viz :

- Part 1 - The Evidence Underlying the 1989 DoE Code of Practice for Agricultural Use of Sewage Sludge (DoE, 1989) and the Sludge (Use in Agriculture) Regulations (SI, 1989).
- Part 2 - Evidence since 1989 Relevant to Controls on the Agricultural Use of Sewage Sludge

The scientific evidence underpinning the 1989 DoE Code of Practice in relation to pathogens, potentially toxic elements (PTEs, also known as heavy metals) and persistent organic compounds was found to be extensive, and more than 200 references were cited. Part 2 of the report addressed the question of whether the controls in the Code of Practice provided an adequate guarantee of microbiological and toxicological safety sufficient to satisfy the increased environmental expectations of the 1990's and beyond, and hence to sustain the practice of recycling sludge to agricultural land. A number of recommendations were made to strengthen the microbiological safety of sludge recycling to agricultural land, which are largely embodied in the "Safe Sludge Matrix" (ADAS, 2001). In addition, it was suggested that further research was needed to determine the survival of specific pathogens (e.g. *Cryptosporium*, *Giardia*, *E. coli* O157) during the sludge treatment process and following land spreading (particularly on grassland), and that the effectiveness of sludge treatment processes should be monitored to ensure that required treatment conditions were being achieved in practice.

The report concluded that the available scientific evidence suggested that the soil limit values for most heavy metals specified in the Sludge Use in Agriculture Regulations (Table 1) were sufficient (and for some metals highly precautionary) to protect soils and crops. Moreover, the on-going research on the long-term effects of heavy metals on soil microbial activity, which commenced in 1994, was thought appropriate to address outstanding issues on this topic (see Section 3.2.3). In terms of organic contaminants (OCs), the report concluded that the consensus international view remained that limits for OCs in sludge recycled to agriculture were not necessary, although it was recommended that the half-lives of selected OCs in sludge treated soils should be determined. Also, additional research was considered necessary to answer questions relating to the uptake of cadmium (Cd) and lead (Pb) by grazing livestock, which had been found to accumulate in offal.

Table 1. Maximum permissible concentrations of potentially toxic elements in soils after application of sewage sludge and maximum annual rates of addition (DoE, 1996).

PTE	Maximum permissible concentration in soil (mg/kg dry soil)				Maximum permissible average annual rate of addition over a 10 year period (kg/ha)
	Soil pH value				
	5.0-5.5	5.5-6.0	6.0-7.0	>7.0	
Zn	200	200	200	300	15
Cu	80	100	135	200	7.5
Ni	50	60	75	110	3
	For pH 5.0 and above				
Cd	3				0.15
Pb[a]	300				15
Hg	1				0.1
Cr	400				15
Mo	4				0.2
Se	3				0.15
As	50				0.7
F	500				20

A concise review of soil heavy metal limits proposed in the third draft of the EC 'Working Document on Sludge' was commissioned by the DETR in 2000 (Davis, 2000). This took the approach that soil metal limits should take into account both risk assessment based on scientific research findings, and application of the precautionary principle. The review was based on the scientific evidence summarised in previous reviews by Carrington *et al*. (1998) and Smith (1996). In summary, Davis (2000) suggested that there should be a single figure metal limit for soils in the pH range 5-7, and that sludge should not be applied to soils of pH<5 (which is consistent with the existing regulations). Higher soil metal limits were considered safe for soils of pH>7 containing at least 5% calcium carbonate (Table 2).

Table 2. Recommended metal limits for sludge treated soil (mg/kg)

Element	Soil pH 5-7	Soil pH >7
Cadmium	3	3
Copper	120	200
Mercury	1	1
Nickel	75	110
Lead	200	300
Zinc	200	300

At the same time, a study of the impacts of introducing the proposed sludge heavy metal limits in the third EC 'Working Document on Sludge' was also commissioned by the DETR (Carlton-Smith, 2000). This assessment was based on sludge quality as reported in the most recent UK Sewage Sludge Survey for 1996/7 (Gendebien *et al*. 1999) and concluded that applying the proposed sludge metal concentration limits would severely restrict the amounts of sewage sludge recycled to land in the UK unless a rapid improvement in sludge quality occurred.

A third DETR-commissioned review following on from the EC 'Working Document on Sludge' looked at the implications of the proposed introduction of concentration limit values for organic contaminants in sludge, and included a survey of organic contaminants in UK sewage sludge (Jones and Northcott, 2000). This review concluded that the introduction of limit values would have very serious implications for recycling of sewage sludge to agricultural land as virtually all European sludges would be likely to exceed the proposed limits. There was found to be little agreement across Europe on whether controls on organic contaminants in sludge were needed, and if so which ones to regulate. The report highlighted that there were still fundamental questions about the scientific justification for such standards, the practicality of monitoring given available analytical techniques, and whether any environmental benefits would result from imposing limit values for organic contaminants.

UKWIR commissioned a critical evaluation (UKWIR Report 02/SL/04/2) of the EC proposal that organic contaminant limit values relating to the application of sewage sludge to agricultural land should be established for some specific classes of compounds (Jones and Stevens, 2002). The report concluded that the majority of sewage sludges would exceed the proposed limit values for linear alkylbenzene sulphonates (LAS), nonylphenol ethoxylates (NPE), polycyclic aromatic hydrocarbons (PAHs) and Di (2-ethylhexyl) phthalate (DEHP), but that since these compounds do not accumulate in soils (LAS, NPE, DEHP) or the terrestrial food chain (PAHs) the proposed limits were difficult to justify scientifically. Whilst the majority of sludge would not exceed the proposed limits for polychlorinated biphenyls (PCBs) or polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs), a screening system developed during the study identified these as priority pollutants. A soil carrying capacity exercise showed that for different sludge application scenarios, background soil levels and half-lives some of these had a marked effect on the rate of accumulation of persistent organic compounds in soil. Moreover, the study recommended that new compounds identified in sludge (e.g. brominated flame retardants) should be evaluated to assess their half-lives in soil and accumulation in the food chain, and that further work was need to improve our knowledge on the effects of sewage sludge on the behaviour of organic compounds in soil.

2.2 EU funded studies

Literature reviews and desk studies on a range of issues surrounding the recycling of sewage sludge to agricultural land have been an important component of EU funded research. Indeed, the EU commissioned a similar review to those funded by DETR and UKWIR in support of the 'Working Document on Sludge' entitled 'Organic contaminants in Sewage Sludge for Agricultural Use' (Langenkamp and Part, 2001). The objectives of this study were to give an overview of OC occurrence in sewage sludge, provide basic toxicological data, assess the persistence of OCs in soils, and undertake a risk assessment for the various pathways and substances. The study identified about 800 published articles and amongst others sources drew strongly on the DETR-funded study (Jones and Northcott, 2000). The report provides a useful summary of the current state of knowledge on OCs and suggested a number of areas for further research.

In 2001, the EU published a report on "Pollutants in Urban Wastewater and Sewage Sludge", a literature review undertaken by Imperial College Consultants (Thornton *et al*., 2001). This study looked in some detail at the sources of heavy metals and organic contaminants in urban wastewater (e.g. run-off rainwater, domestic, commercial source). The pollutant contents of urban wastewater and sewage sludge were reviewed from the existing literature, so that measures to reduce pollution at source could be identified. In addition, a series of recommendations for further research on contaminant sources, fate and behaviour were made.

Another important EU funded study was the Arthur Andersen Consulting report on "Disposal and Recycling Routes for Sewage Sludge" (Aubain *et al*. 2002) which covered the 15 Member States of the European Union and, to a large extent, the Accession Countries. The overall aim of the study was to review current scientific knowledge on the biophysical processes and flows of substances and elements that take place within the 'sludge system', and assess the environmental and economic impact of the main disposal and recycling routes for sewage sludge. Four reports were produced, viz:

- A review of the scientific evidence on the migration and accumulation of substances and elements in the 'sludge system' (Scientific and technical report);
- An assessment of the adequacy of existing legislation dealing with such risks (Regulatory report);
- An economic analysis of the main disposal and recycling routes for sludge (Economic report);
- An investigation of the main factors that limit the use of sludge in the different disposal and recycling routes (Sludge use acceptance report).

The report concluded that the agricultural recycling of sewage sludge makes both economic and environmental sense, provided that the migration and accumulation of substances and elements contained in sludge into the environment and the food chain and the associated risks are reduced and addressed by adequate regulatory measures and good practices. Indeed, the development of agricultural recycling depended largely on improving and increasing confidence in sludge quality. This effectively means preventing pollution of the waste water at source by reducing the amounts of heavy metals and organic compounds entering the waste water sewage system, improving sludge treatment and monitoring sludge quality. The authors noted that these technical solutions require major capital investment for those responsible for waste water, although these costs were relatively low compared to the overall costs of managing urban wastewater.

The report concluded that uncertainty over the potential risks to human health and the environment played a major part in public resistance to expanding various sludge recycling routes. In particular, there was still much uncertainty over the transfer of organic pollutants to the environment and the food chain, and their possible effects. Substantial progress could be made in the social and political acceptance of sludge recycling by promoting research on specific areas of concern, publishing the results and making them widely available. The authors noted that there should be better dissemination of results from current national research programmes on the effects of the agricultural sludge recycling on human health. In parallel, further information was required on sludge composition, sludge production, treatment

and recycling routes, pollution prevention policy measures and external costs (such as human health, ecosystem degradation etc.) to reduce uncertainties and improve the reliability of cost estimates (Aubain *et al*., 2002).

Currently, the EU are supporting 'Project Horizontal' whose main objective is to develop horizontal and harmonised European standards in order to facilitate the regulation of major material streams (e.g. sludge, soil, biowastes etc) in the multiple decisions related to different uses and disposal governed by EU Directives. Horizontal was set up following a workshop on the harmonisation of sampling and analytical methods for heavy metals, organic pollutants and pathogens in soil and sludge in Stresa in 2001 (Gawlik *et al*. 2004). One aspect of the work has focused on pre-normative research required to develop standards needed in the next revision of the regulations. The work was split up in coherent work packages, each addressing an aspect of the standards required by the Sludge, Biowaste and Landfill Directives and in the area of soil analyses. The work packages (WP) were as follows :

- WP1 - Sample collection and preparation
- WP2 - Sampling pre-treatment
- WP3 - Hygienic parameters
- WP4 - Biological parameters
- WP5 - Organic contaminants
- WP6 - Inorganic contaminants
- WP7 - Mechanical properties
- WP8 - Leaching tests
- WP9 - Data handling and interpretation

The first step, which started in November 2002, was the preparation of literature reviews and desk studies on existing standards on the following topics:

- Sampling of sludges, treated biowastes and soils in the landscape
- Enumeration of *E. coli*, *Salmonella*, *Enterococci Clostridium perfringens* and viable helminth ova in sewage sludge and biowastes etc.
- Physical impurities in treated biowaste, weed seeds and plant propagules, and the stability of treated biowaste (respiration method);
- Determination of adsorbable organic halogens (AOX), PCB, PAH, LAS, Nonylphenol (NP) and endocrine disrupters (e.g. phthalates, Di-ethylhexylphthalate (DEHP) and Dibutylphthalate (DBP))
- pH, dry matter/moisture content, organic matter/loss on ignition, total nitrogen, ammonium nitrogen, total phosphorus; extraction of trace elements and determination of trace elements from acid digested samples;
- Flowability, solidity, thixotrophy, stacking behaviour;
- Leaching of sludge, treated biowaste and soils.

The desk study reports are available on the project website (http://www.ecn.nl/horizontal). For some topics, evaluation reports and draft standards are available for consultation.

3. Summary of the research on recycling of sewage sludge to agricultural land

3.1. Sewage sludge use on agricultural land

Robust and up-to-date information on the quantities, types and quality of sewage sludge recycled to agricultural land is needed in order to be able to assess the impacts of sludge recycling on soil quality and function. There have been a number of past surveys of sewage sludge production, treatment and disposal in the UK, with the most recent commissioned by the Environment Agency for the year 1996/7 (Gendebien *et al*., 1999). The key findings were:

- Around 47% (526,000 tonnes dry solids - tds) of sludge produced was recycled to agricultural land in the UK.
- Total UK sludge production was predicted to increase from 1,120,000 t ds in 1996/7 to 1,470,000 by 2005/6 (a 30% increase), with most of the additional amount expected to be applied to agricultural land or incinerated.
- Mesophilic anaerobic digestion (MAD) was the most widely used treatment process.

- Concentrations of PTEs in sludge were comparable to the previous survey in 1990/1, although the mean zinc concentration had reduced by 14%.
- Sludge was applied to about 80,000 ha of land or *c.* 0.5% of the UK agricultural land area. Average application rates were around 6.5 tds/ha (B. Chambers, pers comm). Most soils had a pH greater than 6.0 and PTE concentrations close to background levels.

More recently an EA survey has provided more up to date data on sludge quantities produced, reuse/disposal outlets and sludge quality in England and Wales for the years 2001-2003 (EA, 2004). The total quantity of sludge produced in England and Wales had increased from 967,000 tds in 1996/7 to 1,279,336 tds in 2003, with the amount recycled to agriculture increasing from 480,000 tds in 1996/7 to 802,555 tds in 2003. It was difficult to compare directly the information on sludge heavy metal concentrations with those reported by Gendebien *et al* (1999), as the latter were given as weighted average concentrations by outlet whereas the more recent EA data were national mean values.

3.2. Heavy metals in sewage sludge

3.2.1. The importance of sewage sludge as a source of heavy metals to agricultural land

Defra have funded work to produce an Inventory of Heavy Metal Inputs to Agricultural Soils (Defra projects OC09325, SP0516, SP0547). This has provided quantitative data on sewage sludge metal inputs at a national and field level, in relation to other inputs from atmospheric deposition, livestock manures, fertilisers etc (Nicholson *et al*., 2003), based on the most recent data on sludge metal concentrations available at the time (Gendebien *et al*., 1999). It was shown that sewage sludge generally delivers <20% of total annual heavy metal inputs to agricultural soils in England and Wales (Table 3). However, sewage sludge (applied at 250 kg total N/ha/yr) provided the highest input rate of Zn, Cu, Cr and Hg at an individual field level (excluding canal dredgings and some fungicide applications), Table 4.

Table 3 : Annual heavy metal inputs (t) to agricultural land in England and Wales for the year 2004

Source	Zn	Cu	Ni	Pb	Cd	Cr	As	Hg
Atmospheric deposition	2485	638	180	611	22	84	35	11
Livestock manures	1666	541	47	44	4	32	15	<1
Sewage sludge	394	271	28	106	2	78	3	1
Industrial 'wastes'	65	25	4	7	1	6	nd	<1
Inorganic fertilisers	199	67	30	13	9	94	6	<1
-Phosphate fertilisers	*152*	*22*	*15*	*2.4*	*7.1*	*74*	*5.1*	*<0.1*
Agrochemicals	22	5	0	0	0	0	0	0
Irrigation water	5	2	0	0	0	0	0	nd
Composts	52	13	5	28	<1	6	nd	<1
Corrosion	59	-	-	-	-	-	-	-
Dredgings	615	86	77	152	2	83	22	<1
Lead shot	-	-	-	18000	-	-	-	-
Footbaths	381	0	-	-	-	-	-	-
Total	5944	1648	371	18960	39	383	80	13

nd = no data

Quantitative inventories of heavy metal inputs to agricultural soils are valuable in determining the scale and relative importance of different sources of metals, and along with information on heavy metal inputs are also useful for estimating accumulation rates in soils at the national, catchment and field scale.

Information on losses of heavy metals from soils by crop offtake and leaching is relatively scarce. The heavy metal inventory used crop metal offtake data reported from other studies, but only one figure was available for metal leaching losses from UK soils. This was obtained from a study on heavy metal leaching following sewage sludge application to a grassland soil which was partially funded by the BBSRC (Keller *et al*., 2002).

Table 4 : Heavy metal addition rates (g/ha/yr) to agricultural land in England and Wales from different sources for the year 2004.

Source	Zn	Cu	Ni	Pb	Cd	Cr	As	Hg
Atmospheric deposition	221	57	16	54	1.9	7.5	3.1	1.0
Sewage sludge[a]	4557	3210	335	1256	19	926	34	13
Livestock manures[a] :								
Dairy cattle slurry	1063	281	38	44	1.9	35	14	0.2
Beef cattle slurry	1214	321	43	50	2.1	40	16	0.2
Pig slurry	2321	1679	50	29	1.4	24	7.5	0.1
Cattle FYM[b]	718	168	28	27	2.7	20	12	0.2
Pig FYM	2120	1488	48	27	2.0	22	8.7	0.1
Layer manure	2734	422	47	42	6.1	27	2.2	0.1
Broiler litter[c]	1142	175	20	18	2.6	11	1.9	0.1
Inorganic fertilisers:								
Nitrogen	2.0	1.5	0.2	0.6	0.1	0.5	0.1	<0.1
Phosphate	29	4.1	2.8	0.5	1.3	14	1.0	<0.1
Potash	0.5	0.4	0.0	0.2	0.0	0.1	<0.1	<0.1
Lime[d]	56	12	26	10	1.5	31	nd	nd
Irrigation water	39	16	1.6	0.8	0.1	0.1	1.2	nd
Paper sludge[e]:								
- primary treated	1511	1139	83	248	3	145	nd	3
-secondary biologically treated	1257	1000	96	264	7	165	nd	2
- secondary physically/chemically treated	3167	1580	90	214	3	186	nd	3
Composts[a]	4221	1077	405	2233	14	459	nd	6
Dredgings	159900	22230	20020	39520	520	21580	5590	117
Fungicides								
Hops	12888	2732	-	-	-	-	-	-
Fruit	125	1260	-	-	-	-	-	-
Arable	45	-	-	-	-	-	-	-
Lead shot	-	-	-	2500000	-	-	-	-

nd – no data
[a]Rate of metal addition assuming an application rate equivalent to 250 kg N/ha/yr
[b]Includes sheep FYM
[c]Includes broilers, pullets, other hens and other poultry
[d]Typically applied every 5 years to non-calcareous soils
[e]Calculated using the paper sludge application rates and metal concentrations given in Gibbs *et al* (2005)

3.2.2. Crop yields and heavy metal uptakes

Field studies undertaken in the mid-1990s (Defra project SP0117) showed that past applications of sewage sludge enriched ('spiked') with salts of zinc and copper gave substantial reductions in the yield of both cereals and legumes grown on a sandy soil at ADAS Gleadthorpe (Notts). The results suggested 'critical' topsoil metal concentrations above which yield reductions could be expected of 200 mg/kg Zn and 120 mg/kg Cu, comparable to those currently advised in the UK Code of Practice for Agricultural Use of Sewage Sludge (DoE, 1996). However, yield reductions only occurred when topsoil ammonium nitrate extractable metal levels (a measure of metal bioavailability to plants) were elevated, demonstrating the importance of measuring extractable as well as total heavy metal concentrations in topsoils when assessing likely effects on plant yields and metal uptakes, and setting soil quality criteria (Bhogal *et al*., 2003).

To the best of our knowledge no further work specifically on crop yield responses to heavy metals applied in sludge has been undertaken in the UK in recent years. However, with the introduction of European legislation defining the maximum permissible concentrations (MPC) of Cd and Pb in foodstuffs including cereals (EC, 2001) there has been renewed interest in factors influencing crop uptake of these metals. An HGCA-funded study investigated the relationship between soil properties and the concentration of Cd in wheat and barley grain. Cd concentrations were found to be much lower in barley grain than in wheat grain under comparable soil conditions, with soil total Cd and pH being the most significant factors influencing grain Cd concentrations. A model was developed to predict the likelihood of wheat grain Cd exceeding EU regulations on the maximum permissible concentration of Cd under different soil conditions, particularly in relation to maximum permitted soil Cd concentrations where sewage sludge is recycled to agricultural land (Adams *et al*., 2004). The study also determined Pb concentrations in paired soil and crop samples, but found no significant correlations between grain Pb concentrations with total soil Pb and other soil properties. This indicated the low bioavailability of soil Pb and limited uptake and transport of Pb to grain. It was suggested that the Pb in cereal grain is likely to originate mainly from atmospheric deposition and other routes of surface contamination during harvest and storage (Zhao *et al*., 2004).

In addition to the HGCA-funded work, wheat grain Cd concentrations were determined on plots that had received sludge cake applications as part of the 'long-term sludge' experiment (see Section 3.2.3). Three of the sites also had comparisons with Cd availability from metal amended liquid sludge and metal salts. Grain Cd concentrations were significantly correlated with NH_4NO_3 extractable Cd and soil total Cd. Soil extractability was generally greater in the liquid sludge and metal salts experiments than in the cake experiments, as were grain Cd concentrations. However, across all the sites, NH_4NO_3 extractable soil Cd was no better at predicting grain Cd than soil total Cd. Combining all the data showed that soil total Cd, pH and organic carbon were the only significant variables influencing wheat grain Cd concentrations. A regression analysis predicted that the current UK soil total Cd limit of 3 mg/kg was not sufficiently protective against producing grain above the EU grain MPC of 0.235 mg Cd/kg dry weight, unless the soil pH was > 6.8. However, the predictions showed that grain would be below the MPC with >95% confidence with the proposed new EU draft regulations permitting maximum total Cd concentrations in soils receiving sewage sludge of 0.5 mg/kg for soils of pH 5 – 6, 1 mg/kg or soils of pH 6 – 7, and 1.5 mg/kg for soils of pH ≥ 7. (Chaudri *et al*., in press)

3.2.3 Effects of heavy metals on soil microbial activity

The 'historic' sludge experimental sites at ADAS Gleadthorpe (Notts) and Rosemaund (Herefordshire) were used to evaluate the effects of heavy metal additions in sewage sludge on soil heavy metal availability, nitrogen mineralisation and soil microbial activity (Defra project SOP0128). There were no consistent changes in topsoil ammonium nitrate extractable metal (Zn, Cu, Ni & Cd) concentrations at Gleadthorpe or Rosemaund between 1994 and 2000, suggesting that the soils were in equilibrium in terms of heavy metal bioavailability. The soil metal availabilities at Rosemaund were similar to sites which had a history of sewage sludge additions, but those at Gleadthorpe were much higher and represented a 'worst-case'

situation in terms of likely heavy metal availability. Elevated topsoil Zn concentrations at Gleadthorpe and Rosemaund had no effect on N mineralisation or soil respiration (a measure of microbial activity), and similarly elevated Cu concentrations had no effect on soil respiration rates, suggesting the presence of metal-tolerant microbial populations. However, at both Gleadthorpe and Rosemaund, soil N mineralisation decreased with increasing Cu concentrations.

Initial assessments of the impact of heavy metals from sludge on soil microbial populations at Woburn showed that both numbers of some rhizobia species and their diversity decreased as soil metal concentrations increased. Furthermore, soil populations of *Rhizobium leguminosarum* biovar *trifoli* (which fix atmospheric nitrogen in symbiosis with clovers) and pea/bean rhizobia at Braunschweig (Germany) were shown to be sensitive to soil zinc from past applications of sewage sludge at metal concentrations below the UK statutory limits (Defra projects SP0112, SP0120).

From this early work, it was not possible to identify unequivocally which of the metals, or concentrations of metals, present in sewage sludge was responsible for the detrimental effects observed on crops and soil microbial populations. Indeed, an Independent Scientific Committee Reviewing the Soil Fertility Aspects of Sludge Application to Land (MAFF/DOE, 1993) recommended that "further research was needed to examine the effects of heavy metals from sewage sludge on soil micro-organisms" and that "field trials should evaluate sludge cake and metal-amended liquid sludge metal additions (and inorganic metal salts) on soil micro-organisms under controlled conditions", with the "sites providing a long-term resource for use in controlled comparative experiments". In response to the recommendations of this report and in order to continue the development of soil protection policy where sewage sludge is applied to agricultural land, Defra (with UKWIR, WAG, EA and SEERAD) funded the establishment of nine long-term sites throughout Britain where sewage sludge was applied over 3-4 years up to 1998 (Defra projects SP0105, SP0109, SP0111, SP0125, SP0130, SP0131, WT04001, WT04002, WT04005). The sites provide a series of individual zinc, copper and cadmium dose-response treatments that cover the soil metal concentration range from 'background' levels to beyond the maximum permitted limits for topsoils (SI, 1989). An additional experiment at three of the sites, where zinc, copper and cadmium carbonate salts were added to soils, provides a contrast in the form of metals applied and enables the importance of organic matter additions in mediating metal bioavailability to be evaluated (Defra projects SP0114, SP0126, SP0133). *Although statistically significant responses in soil microbial populations were apparent during phase II of the study (1998-2002), and the body of evidence is growing, the results to date indicate no consistent metal effects on microbial activity that could unequivocally be attributed to metal toxicity per se. Further soil sampling and measurements during phase III (2002-2006) of this long-term study will help to establish whether the effects measured so far are consistent and true.*

In Scotland, a SEERAD funded project (SCR/901/02) investigated the effects of applications of heavy metal-contaminated sewage sludge on measures of soil biological and physical resilience at the Auchnicruve site (Ayr) which is part of the network of long-term sludge experimental sites (Griffiths *et al*., 2005). Soil total carbon and dissolved organic carbon (DOC) levels were greater in the sludge treated soils, but there were no differences due to heavy metal contamination. However, the rate of DOC mineralisation was increased in the Zn contaminated soil and reduced in the Cd contaminated soil. Effects on soil physical resilience were found in the Cd and Cu contaminated soils and pointed to changes in soil aggregation. The authors suggested that soil physical and biological resilience are coupled through the soil microbial community.

3.2.4. Uptake of heavy metals by grazing livestock

Uptake by livestock grazing on contaminated soils is one route by which heavy metals can enter the human food chain. Experiments where lambs were grazed on land that had received past sludge applications and was close to the statutory soil limit for Cd (3 mg/kg) found little evidence of metal accumulation in muscle tissues. However, there was significant accumulation of Cd and Pb in the animals' liver and kidneys, with the Pb concentration in the liver of lambs grazed on the highest sludge application rate soil approaching the statutory limit

for food of 2 mg/kg fresh weight (Hill *et al*., 1998a). However, this was a 'worst case' situation and was thought unlikely to have human health implications even for people who regularly consume offal as part of their diet (Defra project SP0107). More recently, researchers at the Macaulay Institute looked at the accumulation of PTEs in the liver tissue of sheep grazed on sewage sludge treated pastures (Rhind *et al*., 2005a). The authors concluded that repeated sludge applications (5 years) to pasture were associated with altered, but not necessarily increased rates of PTE accumulation in liver tissue. Accumulation rates depended on the PTE and were probably influenced by route and duration of exposure, whereas the research suggested little effect of climatic conditions and herbage growth.

A MAFF-commissioned desk study (Nicholson, 1999) looked in detail at the importance of different potential sources of Cd and Pb to the diets of grazing livestock. This study showed that soil ingestion was an important source of Cd and Pb for all livestock classes and that sewage sludge applications could increase overall uptake of these metals by grazing livestock despite the imposition of no grazing periods. A number of practical techniques for minimising soil ingestion were suggested.

Other studies have looked at potential methods to reduce or remove heavy metals from the food chain using sorptive minerals (MAFF/FSA project FS2190) or non-food crop species (MAFF/FSA projects FS2196 and FS2197). In addition, the EPSRC have funded research to investigate a novel non-invasive remediation technology for the containment of heavy metals in contaminated soils (EPSRC grant number GR/L96592/01). The technique involved the use of sewage sludge conditioned with natural zeolites for the immobilisation of heavy metals. The research also investigated the extraction of heavy metals from sewage sludge using this technique to potentially enhance its suitability for agricultural re-use .

3.3. Organic contaminants.

3.3.1 Organic contaminants in sewage sludge and soils

Following some initial problems measuring dioxin levels in soils (Defra project SP0116), research on persistent organic pollutants - POPs (Defra projects SP0103, SP0113) showed that whilst concentrations of dioxins and furans were increasing in soils due to deposition from the atmosphere, concentrations were likely to be increased about a thousand times faster where sewage sludge was applied. In contrast, concentrations of polychlorinated biphenols (PCBs) in soils were decreasing but were five times higher where sewage sludge had been applied (even 30 years after applications had ceased) than in an untreated control soil. However, because PCBs are strongly bound to soils and are insoluble they are unlikely to be biologically active or available for crop uptake, and were not considered to constitute a direct risk to the human food chain. Adding pure organic compounds to soil to mimic different groups of organic pollutants found in sewage sludge, showed that none had any significant direct toxicity to soil microbes. However, the potential effects of their microbial degradation products over a long time period were not tested.

A major focus of UKWIR directed research work has been detailed investigation of the quantities, fate and behaviour of organic contaminants (OCs) in sewage sludge. The research programme commenced with a project to identify priority OCs in sewage sludge (UKWIR report 96/SL/03/1), which collated published literature on over 300 organic compounds. Likely inputs of OCs to agricultural soils were determined and results compared against soil quality standards. A screening approach was developed, based on compound physico-chemical properties, to assess the likely behaviour and fate of chemicals introduced into agricultural soils in sewage sludge. The propensity for compounds to leach to groundwater or transfer to crop plants and grazing animals was assessed, with the 'sludge-soil/herbage-livestock' pathway identified as the most important with regard to potential human exposure of sludge-derived OCs (see Section 3.3.3). Routine operational practice for the application of sewage sludge to land was regarded as very unlikely to result in UK soil quality limits for OCs being exceeded. However, repeated applications of sludge to pasture land result in the accumulation of OC levels which are of potential concern in the long term. Surveys of digested sludge from 14 UK treatment works were also undertaken (Jones and Northcott, 2000; UKWIR report 01/SL/03/04) to obtain contemporary data on the concentrations of

certain classes of organic compounds in order to assess whether UK sludges were likely to comply with the limits proposed by the EU in the 'Working Document on Sludge' (see also Stevens *et al*., 2003).

A further study then looked in more detail at pentachlophenol (PCP) and chloranil based dyes and pigments as potential sources of dioxins and furans (PCDD/F) in sewage sludges (UKWIR report 97/SL/04/1). The potential for PCDD/Fs derived from these sources to persist in sludge amended soils and transfer into the agricultural food chain was also investigated. It was noted that the application of other types of organic amendments (e. g. livestock manure, paper waste sludge and textile waste) could represent important sources of PCDD/Fs to agricultural soils, and that the application of these 'wastes' was not subject to the same levels of control as sewage sludge. As a result, levels of PCDD/Fs in livestock manures were later quantified and compared with sewage sludge (Stevens and Jones, 2003), Table 5. The authors concluded that the application of sewage sludge and cattle manure to agricultural land at current rates does not make a significant contribution to human exposure to PCDD/Fs.

Table 5. Concentrations of PCCD/Fs in UK sewage sludge, livestock manures and greenwaste compost (toxic equivalent - TEQ ng/kg ds)

	Range	Mean
Sewage sludge[1]	8-225	59
Livestock manures[2]	0.19-20	-
Greenwaste compost[3]	1.2-34	17[*]

[1]Jones and Stevens (2002)
[2]Stevens and Jones (2003)
[3]Defra (2004)
[*]'Best estimate'

Researchers at Lancaster University also investigated the behaviour of sludge derived volatile organic compounds (VOCs) and PAHs in soils and on grassland. Laboratory experiments with VOCs showed that volatilisation was the predominant loss process, with loss rates depending on sludge application rate and method, soil properties and the compound characteristics. The majority of sludge derived VOCs volatilised in less than 10 days after application and as a result the potential for transfer to the foodchain was assessed to be low (Wilson and Jones, 1999). Lighter PAHs were also rapidly lost from the grassland soil surface primarily by volatilisation. Loss rates for the heavier PAHs were slower, with rain playing an important role in compound degradation and growth dilution reducing levels in herbage (Kilian Smith *et al*., 2001).

Several UKWIR-funded studies have looked at the fate and behaviour of endocrine disrupting substances (EDS) in sewage treatment plants (UKWIR reports 01/TX/04/3 and 01/TX/04/2). Recently research has developed a new method for determining the oestrogenicity of endocrine disrupting compounds in sludges and soils (UKWIR report 01/TX/04/8). The studies indicated that oestrogenic compounds in sludge do not leach into groundwater and are not bio-available to crops/livestock when applied to land. Research is continuing in this area via an UKWIR-funded research project to co-ordinate national research on endocrine disrupting substances.

More recently, a Defra-funded project (SP0547) has provided a very comprehensive review of the literature on organic contaminant inputs to soils in sewage sludge, their behaviour in soils and effects on soil function.

3.3.2 Uptake of organic contaminants by food crops

The FSA are funding a research programme which aims to understand the pathways by which organic contaminants enter food, the levels at which they occur, and the mechanisms by which they accumulate in the food chain. A number of the projects have looked specifically

at organic contaminants applied to agricultural land with sewage sludge. For example, Imperial College examined the potential of detergent residues (alkylphenols) to enter the food chain following the application of sludge to land (FSA project C01029). The study identified the principal breakdown products of nonyl phenyl ethoxylates (NPs) in sewage sludge and then investigated their fate in soil and potential for plant uptake. Overall, the results were consistent with previous studies and showed that while NPs can enter some crops following sewage sludge application, the amounts found in edible portions of the plant pose no risk for human health. Research at Wye College (FSA project C01001) looked at methods to further reduce the potential for OC contamination of food grown in sewage sludge amended soils using simple measures, viz: a) enhanced treatment of sewage sludge by thermal drying or composting prior to use; b) controlled timing of crop sowing relative to sludge application to soil; and c) applying the sludge to soil during long spells of dry weather. Sludge 4-nonylphenols and phthalates were readily lost during composting thus amounts applied to the soils were substantially lower than from conventionally treated sewage sludge. Soil 4-nonylphenol and phthalate contents were also much reduced by applying conventionally treated sludge several months before sowing, although reductions were not as great as by composting. In contrast, the type of sludge treatment process had little effect on soil PCBs, which were approximately doubled by sludge application. Movement of PCBs, phthalates and 4-nonylphenols from soils into food crops was very limited. Consequently, it was not possible to provide conclusive evidence that either the sludge treatment method or the timing of soil application would further reduce the potential transfer of these OCs to food crops. Studies with variable soil moisture contents (related to sowing during long spells of dry weather) indicated differences in potential OC transfer to crops; however, these differences were small and the results were inconclusive.

Underpinning research work on OCs in soils and food crops is provided by the UK soil herbage survey (FSA project C01034). This project, co-funded by the FSA, EA, Defra, NAW, EHSNI, SEPA and SNIFFER, will provide a national overview of the chemical contamination (dioxins, PCBs, PAHs) of soil and herbage, as a baseline for comparison to specific sites and will allow an assessment of changes in soil and herbage chemical quality since previous surveys.

3.3.3 Uptake of organic contaminants by livestock

The direct ingestion of sludge-treated soil by grazing livestock is considered to be the principal route of PCB and PCCD/F accumulation in the food chain from the agricultural use of sewage sludge (Smith, 1996). A large body of work has been funded by MAFF and subsequently the FSA, in particular looking at the transfer of these compounds into meat, milk and other foods (MAFF/FSA projects FS2150, FS2151 and FS2176).

Recently, researchers at the Macaulay Institute studied the accumulation of alkyl phenols and diethylhexyl phthalate (endocrine disrupting compounds) in tissues of sheep grazed on sewage sludge treated pastures (Rhind *et al*., 2005b). The authors concluded that the addition of sewage sludge to pasture was unlikely to cause large increases in tissue concentrations of these OCs in sheep and other ruminants.

3.4. Pathogens

Sewage sludge and other organic manures (e.g. livestock manures, composts) can potentially contain a number of human, animal and plant pathogens. The FSA recognised that there was a potential risk of pathogen transfer from organic ‘wastes’ to the food chain and set in place a structured programme of research and risk assessment into the use of *all* organic ‘wastes’ on land. The FSA and Defra-funded research concentrated on pathogens in livestock manures. Nevertheless, the generic findings are relevant to sludge recycling in agriculture and are summarised in Section 3.4.2. An aligned research programme directed by UKWIR (see below) investigated the effect of various sewage sludge treatment methods and the survival of sludge borne pathogens in the environment.

3.4.1. Pathogens in sewage sludge

Analytical methods. Following an initial review of current analytical methods for determining pathogens in organic 'wastes' (UKWIR report 98/SL/06/2), a generic method for the enumeration of bacterial pathogens was developed which provided a robust platform for pathogen measurements in sludges and soils (UKWIR report 00/SL/06/5). Not only did the new methods allow enumeration of the target pathogens in the presence of high background levels of microorganisms, but they were also applicable to a wide variety of organic 'wastes' (e.g. livestock manures, see Section 3.4.2).

Sludge treatment. A survey was undertaken to assess the effects of different sludge treatment processes on numbers of *Escherichia coli* in sludges from all parts the UK (UKWIR report 99/SL/06/3). All of the processes surveyed reduced the numbers of *E. coli*, with composting, lime addition and thermal drying reducing numbers to below the analytical limit of detection. Mesophilic Anaerobic Digestion (MAD), the process carried out at the majority of sites surveyed, resulted in an average log reduction in *E. coli* numbers of 1.4 for liquid digested sludge and 2.3 for digested sludge cake. However, the resulting sludge still contained relatively large numbers of bacteria : the average log concentration of *E. coli* in digested sludge cake was 6.7 compared with the average log concentration of untreated sludge of 8.9 (Humphrey, 1999a). A subsequent project confirmed that MAD could reduce *E. coli* numbers by up to 4 orders of magnitude (UKWIR report 99/SL/06/4, Humphrey, 1999b). Further research evaluated the survival of a number of enteric pathogens added to sewage sludge in a range of treatment processes (MAD, lime stabilisation and composting). Indigenous *E. coli* were shown to have similar survival properties to the verotoxigenic strain *of E. coli* O157 and could act as an suitable indicator for this pathogen (UKWIR report 02/SL/06/6). Parallel EU funded research included a study on the "Evaluation of Sludge Treatments for Pathogen Reduction" (Carrington, 2001). This report identified for different types of sludges those pathogens that may present a risk to human, animal or plant health. It considered the factors in sludge treatment processes, particularly the newer processes, that would 'kill' pathogens, and made recommendations on the parameters to be applied to these processes to produce treated sludges that had low pathogen levels. Constraints on the use in agriculture of sludges not subject to enhanced treatment were also discussed, and measures proposed for the quality assurance of treated sludge and the validation of treatment processes and new treatment plants.

Survival in soil. A research programme funded by the Engineering and Physical Sciences Research Council (EPSRC) and conducted by Imperial College, included experimental work to provide reliable information on the presence and persistence of pathogens in sewage sludge after land spreading. A series of field trials showed that the application of enhanced treated biosolids (thermally dried or composted) did not contribute *E. Coli* to the indigenous soil pool, whereas conventionally treated biosolids (anaerobically digested) increased *E. Coli* numbers above ambient levels (Lang *et al*., 2003). However, survival was limited to *c*.3 months irrespective of environmental conditions or numbers of *E. Coli* added to the soil. Current jointly funded research (UKWIR, EPSRC, Defra) with Imperial College aims to increase understanding of the fundamental ecological processes involved in the decay of enteric microorganisms in sludge-amended agricultural soil. Through extensive field trials, the research will focus on quantifying the intrinsic ecological dynamics that exist in the soil environment that are directly or indirectly responsible for the suppression of enteric microorganisms added to soil in sludge. The field experiments are also supporting investigations to determine the microbiological controls on N release from different types of conventional and enhanced-treated biosolids to provide a sound scientific base to support the agronomic use of these products (see Section 3.7).

A BBSRC grant studied the 'Persistence and Movement of Verotoxin Producing *Escherichia coli* 0157:H7 in Soil'. The work aimed to assess the survival and dispersal of microbial pathogens derived from organic 'wastes' (animal and sewage sludge) within the environment, and found that sub-surface injection (25cm) of organic 'wastes' into soil may reduce the risk of pathogen persistence in the environment (Avery *et al*. 2004).

Risks to health. A microbiological risk assessment was undertaken by WRc-NSF to quantify the risks to humans from consumption of root crops grown on land to which treated biosolids had been applied in accordance with the "Safe Sludge Matrix" and the Sloudge Use in Agriculture Regulations (UKWIR report 03/SL/06/7). The predicted risks to the UK population as a whole were extremely small and it was suggested that a 12 month harvest interval would compensate for any increased risk due to inefficient sludge treatment.

Plant pathogens. In parallel with the research on human pathogens, work has also studied the role of sewage sludge as a potential vector of plant pathogen transmission. Potato brown rot is a disease caused by the bacterium Ralstonia solanacearum which can seriously damage potato production and which has quarantine status in Europe to restrict its spread. A 3-year SAPPIO LINK project (LK0909) led by CSL was undertaken to assess the potential risks of spreading potato brown rot through the application of sludge to agricultural land, and to adopt appropriate monitoring and control measures where necessary. The project produced practical guidelines to assist the water industry in assessing and monitoring the risks of spread of the brown rot bacterium where infected crops were inadvertently imported and processed. Overall the project concluded that there was a negligible risk of the brown rot bacterium being transmitted to agricultural land through the application of sewage sludge or through discharges of sewage effluent into watercourses, provided that all the sewage sludge was adequately treated by conventional means.

3.4.2. Pathogens in livestock manures and other organic 'wastes'

Against a background of increases in food borne illness in the UK, a review was undertaken by ADAS and CAMR (MAFF project FS2526) on farm manure applications to agricultural land and an assessment of the risks of pathogen transfer into the food chain (Nicholson *et al*., 1999). The report summarised current knowledge on the levels and prevalence of *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, *Escherichia coli* O157, *Cryptosporidium parvum* and *Giardia intestinalis* in livestock manures, and the factors which affect their survival during manure storage, in soils and on crops after land application. Using this information, along with knowledge of current farm manure management practices, an assessment was made of the risks of manure pathogens being transferred into the food chain. The report summarised a number of practical measures that could be used to minimise the risks of pathogen transfer from livestock manures into the food chain including manure treatment, extended storage and no harvest periods following land spreading (see also Nicholson *et al*., 2004).

The FSA funded research with WRc to assess the risks to food safety associated with spreading of animal manure and abattoir 'wastes' on agricultural land (FSA project B17002). The project developed a tool for assessing risks to food safety from farm 'waste' management strategies by constructing a conceptual model of 'waste' usage and the pathways through which humans and livestock could be exposed to selected pathogens. Event tree models predicting pathogen loadings on crops at harvest were developed for several types of manure. However, the work identified some gaps and shortcomings in the available input data that influenced the validity of the risk assessments. In particular, there was uncertainty over the levels of certain pathogens in livestock manures and there was a need for more detailed information on the decay rates of pathogens in stored manures and after land application.

Following on from this, a series of field studies on pathogen survival during livestock manure storage and following land spreading were commissioned with ADAS and CAMR (MAFF/FSA project BO5003). The work started with the validation of laboratory techniques to enumerate enteric pathogens found in the main types of livestock manures produced on British farms. These techniques were then used to determine the levels of pathogens in fresh and stored livestock manures from farms throughout Britain. The survival of pathogens during manure storage and following land spreading was investigated using both controlled laboratory experiments and farm scale storage and land spreading experiments, so that pathogen survival curves could be produced and the factors which affect survival determined. The study showed that *E. coli* O157, *Salmonella* and *Campylobacter* survived in stored slurries and dirty water for up to 3 months, with *Listeria* surviving for up to 6 months. In contrast, these pathogens survived for less than 1 month in solid manure heaps where temperatures greater

than 55°C were obtained. Following manure spreading to land, *E. coli* O157, *Salmonella* and *Campylobacter* generally survived in the soil for up to 1 month after application, whereas *Listeria* commonly survived for more than 1 month (Nicholson *et al*., 2005). This information has subsequently been used to inform the draft FSA guidance note for farmers on "Managing Farm Manures for Food Safety : Guidelines for Growers to Minimise the Risks of Microbiological Contamination of Ready to Eat Crops".

Defra-funded research then moved on to consider in more detail the routes and risks of pathogen losses to the wider environment. Field experiments studying the transport of microbial pathogens to water aimed to study 'worst-case' risk scenarios following the land spreading of manures and during cattle grazing (Defra project WA0804). Drainage waters from fields grazed by cattle or where manures had recently been applied were shown to contain *E.coli* concentrations which exceeded the EC limit (1976) for bathing water quality (2000 colony forming units/100 ml). Also, *E. coli* was detected in surface runoff collected during grazing and following recent manure applications. The transmission of pathogens via aerosol dispersion during slurry spreading was also investigated, with projections indicating that some pathogens could be transported up to 1500m.

The effectiveness and reliability of measures to control pathogen losses from livestock manures/excreta to the wider environment were examined in Defra project WA0656. In the case of 'point source' loss routes, investment in farmstead runoff collection and storage systems was assessed to be the most cost-effective approach. For handled manures, extended storage periods or treatment were suggested as the most practical and cost-effective options. This work highlighted that, in developing manure management policies to minimise the risks of pathogen transmission to the wider environment, there was a need to consider the potential knock-on effects on nutrient emissions to the air and water environments.

Organic manure-borne pathogens can also impact on bathing water quality and shellfish beds, particularly in the north-west and south-west of England, where there are 'flashy' river systems (i.e. rivers which respond rapidly to rainfall events but also return quickly towards baseflow) and large numbers of intensively grazed livestock (especially dairy cows). The FSA commissioned work with ADAS and CEFAS to evaluate the contribution of organic 'wastes' spread on agricultural land and sewage treatment works to pathogen loads reaching shellfish production beds in estuaries (FSA projects B05006/B05007). A catchment level model, Coliform Source Apportionment Tool (CSAT), was developed and estimated that point sources were responsible for more than 95% of the annual faecal coliform (FC) load exported from two study catchments on the south coast of England. However, during storm events, diffuse (manure-related) sources were estimated to contribute up to 80% of the loading. Also, recent research by ADAS and CREH (Defra project ES0140) provided a preliminary estimate of the relative contributions of agricultural and urban sources to faecal coliform (FC) inputs to coastal bathing waters in England associated with the failures under the Bathing Water Directive. These results indicated that the overall diffuse agricultural contribution to the total bathing season FC budget was *c.*30% for the three problem bathing water clusters studied in north-west and south-west England and in Yorkshire/Lincolnshire.

3.5. Radionuclides

The recycling of sludge to land as a potential pathway for radionuclides to soil and food has been investigated in a number of projects funded by the EA, FSA (Project RP0441) and NRPB.

In a study of the potential for sewage sludge to affect radionuclide concentrations in soil, Ham *et al*. (2003) introduced a screening approach based on radioisotopes expected to be discharged in waste water and their associated half lives. Drawing on data compiled by Titley *et al*. (2000), an estimate was made of the potential impact of radionuclides in sewage sludge from the Beckton waste water treatment works under a scenario where the sludge was applied to agricultural land (rather than incinerated as is currently the case). The results indicated that in general the effects were unlikely to be detectable or only a few times above detection limits. However, a key step in such analysis is the solid/liquid partitioning that occurs

during the treatment process, generally characterised by the linear equilibrium partition coefficient (K_d) for which there are limited data (Thorne and Stansby, 2002). Thorne and Stansby (2002) concluded that there was a requirement for further experimental studies at the pilot-plant scale and through the derivation of empirical parameter values from monitoring at operating plants. Indeed, a current EA funded project (SC020150) aims to build on existing information to provide improved and more robust data on radionuclide partitioning.

3.6. Nutrient losses to the environment

3.6.1. Nitrogen

Nitrate leaching. In the early 1990's a substantial body of work was undertaken quantifying nitrate leaching losses following sewage sludge applications to agricultural land. Results from the DoE funded study showed on a sandy arable soil that the earlier in autumn sludge was applied, the greater the amounts of nitrate leaching losses (Shepherd, 1996). Similarly at a grassland site, greater leaching losses were measured after autumn than winter sludge applications (Misselbrook *et al*., 1996). In both experiments, liquid digested sludge (which had a large proportion of its N content in the ammonium-N form) presented the greatest nitrate leaching risk. Nitrate leaching losses were also exacerbated by the deep injection of liquid sludge into soil compared with surface broadcast application.

Ammonia. Shepherd (1996) referred to indirect evidence of ammonia volatilisation and denitrification losses following sewage sludge applications. We were only able to identify one study on ammonia emissions from sludge spreading funded by Anglian Water. The study had the primary objective of measuring odour emissions from sludge spreading using an improved liquid sludge injection system, but also found that the improved system was effective at reducing ammonia emissions compared with the 'standard' injection system (Moseley *et al*., 1998). Most of the research effort to date has concentrated on measuring ammonia losses from livestock manure management systems, largely due to the much greater amounts produced annually (*c*.90 million tonnes of livestock manure compared with 3-4 million tonnes sludge). Where estimates of ammonia emissions from sludge have been needed (e.g. MANNER – Chambers *et al*., 1999), these have been based for liquid sludges on pig slurry emissions and for solid-based sludges on farmyard manure emissions. In the UK Ammonia Emissions Inventory, emissions from sewage sludge spreading were estimated using a 'best loss estimate' for livestock manures (25% of the readily available N applied), backed up by a single measurement of ammonia emissions from sludge (27% of the readily available N applied) made in the US (Sutton *et al*., 1995; 2000). The UK Ammonia Emissions Inventory (year 2000) estimates that of the 320 kt of ammonia (NH_3) emitted, only 6.1 kt were from sewage sludge treatment and spreading (Defra, 2002). However, this may be an underestimate as it was made at a time when much greater quantities of liquid sludge were applied to land, which could be injected into the soil and thereby reduce ammonia emissions compared with the application of solid products which are more widely used at present. Similarly, modern treatment methods (e.g. thermal drying, lime stabilisation, composting etc.) are also likely to have resulted in increased levels of ammonia emissions.

Denitrification. There have been few measurements of gaseous N losses by denitrification. However, a recent study (Defra project CC0246) included measurements of N_2O losses from liquid digested sludge, together with pig and cattle slurry and inorganic N fertiliser. The study concluded that there was insufficient evidence to support separate N_2O emission factors for sewage sludge compared with farm manures, although the composition of the organic material would intuitively effect N_2O emissions and more research was required to substantiate these findings. Also work funded by the Water Industry is presently being undertaken by Reading University/IGER/WRc measuring nitrous oxide and methane emissions following sludge application to land.

3.6.2. Phosphorous

The environmental impact of phosphorus (P) from the agricultural recycling of sewage sludge and its potential contribution to the eutrophication of surface waters has been a major focus of research for a number of years. The programme of work started with a literature review of the

significance of sewage sludge as a source of P loss from agricultural land to surface waters (UKWIR report 95/SL/02/1). A comprehensive series of experimental studies was then commissioned to investigate the environmental impact of P from the agricultural use of sewage sludge (UKWIR report 00/SL/02/05), viz:

- the amounts, form and bioavailability of P in sewage sludge
- the accumulation and migration of P in sludge amended soil
- P leaching from free draining soils receiving sewage sludge
- P losses from drained clay soils
- P loss in surface run-off from sludge-amended soil
- P cycling in soils receiving sewage sludge

More recently a joint Defra/UKWIR/EA funded project has reviewed the measures available to limit and control phosphorus losses following sludge application to land. A preliminary methodology for assessing the risk of P loss to watercourses has been developed - the Phosphorus Loss Risk Index (PLRI) – based on soil erosion risks and the risk of P build-up in soils. Also, ongoing experiments are looking at the build up of P in soils from 'new' sludge products which are rich in iron (Fe) or calcium (Ca). The aim of the project is to produce simple practical guidance on the rate and timing of biosolids applications in different PLRI areas (UKWIR report 05/SL/02/6).

In addition, EPSRC funded the SEAL project which investigated whether it was possible to minimise phosphorus losses by applying sludge to land outside critical source areas regardless of the soil phosphorus status (EPSRC grant numbers GR/N26074 and GR/S59246/02). The research aimed to develop a predictive and spatially-sensitive semi-distributed model of critical thresholds for sludge application that goes beyond traditional 'end-of-pipe' or 'edge-of-field' modelling, to include delivery to receiving waters from non-point sources at the river basin scale. The research output was synthesized in an advice matrix (the Nutrient Export Risk Matrix - NERM) for end-users, to determine the most appropriate form and frequency of spatially-sensitive sludge applications to land to achieve sustainable sludge management without detriment to the environment and receiving water quality (www.lec.lancs.ac.uk/cswm/seal). More details of the NERM can be found in Hewett *et al.* (2004).

There is no indication from this research that P applied in sewage sludge behaves in a different manner to P applied with livestock manures, thus management practices required to minimise P losses to the environment should not need to be different.

3.7. Fertiliser value of sludge

Research to increase the economic efficiency of sludge and farm manure nutrient inputs and cereal crop production, whilst minimising environmental impacts, was undertaken as part of the Defra SAPPIO-LINK programme (LK0904). The project focused on (a) better quantification of N mineralisation from dewatered sludge cake and composted products and (b) shifting applications of liquid manures (sludges and slurries) from autumn to spring, thereby increasing their N fertiliser replacement value. It was shown that the fertiliser N replacement value (% of total N applied) was greater for the sludge cake than the composted sludge, but was not affected by application rate. Of the organic fraction mineralised in the first year, around 15% was measured for fresh dewatered cakes and 5% for composted materials. There were also measurable residual effects in the second and third years. Breakdown was related to thermal time, with laboratory incubations a good guide to whether the materials were likely to be 'slow' or 'quick' mineralisers. The small plot experiments clearly demonstrated that liquid manures could be top-dressed in spring to cereal crops, thus reducing nitrate leaching risks and increasing their fertiliser N value (Shepherd and Smith, 2000; Smith and Shepherd, 2000; Smith and Chambers, 2001; Shepherd and Smith, 2002).

The short-term and residual N and P value of conventional and enhanced treated biosolids currently recycled to farmland was assessed in a 3 year programme of field trials with ryegrass, co-funded by the EPSRC (Morris *et al*., 2003; Smith & Bellet, 2001; Smith *et al*., 2002; Smith *et al*., 2003). Tentative fertiliser N replacement values (ranging from 30-35% of the total N applied) were proposed, with thermal treatment processes increasing the

mineralisable N fraction. There was little residual N availability in the year after application. P availability from conventional digested biosolids was 50% of that from water soluble fertiliser, but increased with thermal treatment (100% of water soluble P) and was 2-3 times higher than water soluble fertiliser for liquid sludges. Supplementary laboratory incubation studies were conducted to describe the kinetics of N mineralisation as a basis to predict the N fertiliser value of a range of biosolids products (Breedon *et al*., 2003).

In addition a number of studies on the agronomic implications of sludge use in agriculture have been undertaken by individual water companies. The results of many of these studies are not in the public domain, however, some findings have been published in the scientific literature. For example, an incubation study funded by Thames Water Utilities Ltd aimed to determine the P release characteristics (and hence P fertiliser replacement value) of sludge from P removal and advanced treatment processes (Smith *et al*., 2000a). Biological P removal processes increased P extractability, whereas iron enrichment had little or no effect. However, thermal drying decreased P extractability by 19-62% and this was enhanced if the sludge was also enriched with iron. The same study also investigated the effects of thermal drying on the N fertiliser value of sludge (Smith *et al*., 2000b). Thermally dried and anaerobically digested sludges were as effective as conventional dewatered digested sludge cakes in supplying crop available N, even though thermal drying decreased the readily availble N content.

A Defra Horticulture Division funded project is investigating the sustainable phosphorus fertilisation of potatoes (Defra project HH3504SPO). Preliminary observations have indicated that struvite [$(NH_4)Mg(PO_4)\cdot 6(H_2O)$], which precipitates out of sewage sludge and can be reclaimed from livestock manures, can provide an alternative to inorganic P fertilisers for crop production. Struvite disposal in landfill is expensive and hence the use of struvite as a fertiliser is an attractive proposition. One aim of this ongoing project is to assess the potential of struvite as a P fertiliser for potatoes and to compare its effectiveness in field trials with water soluble triple super phosphate fertiliser.

Finally, a review was undertaken of the sulphur (S) and magnesium (Mg) fertiliser value of sewage sludges (UKWIR report 97/SL/06/1). A survey found that UK sludge typically contained about 1 % S in the dry solids (DS), of which approximately 10-15 % was in an extractable or readily ‘plant available’ form. Sludges were shown to supply more S than livestock manures at equivalent rates of N application. The average content of Mg in sludge was about. 0.4 % in the DS. Although sludges generally contained lower amounts of Mg than livestock manures, they still provide useful quantities of Mg for crop uptake (Nicholson *et al*., 1997).

3.8. Soil Quality

Regular applications of sewage sludge will lead to slow but progressive increases in soil organic matter (OM) content. Soil OM can influence a number of soil physical, chemical and biological properties, which in turn have a positive impact on soil quality and fertility. UKWIR funded a literature review (UKWIR report 99/SL/08/01) and field studies at 7 sites in Britain where different types of sludge products had been applied for 4 years at cumulative rates above the minimum level reported in the scientific literature (*c*.10 t/ha dry solids or 5 t/ha OM) for detectable effects on soil physical properties (UKWIR report 01/SL/08/2). The field studies showed a trend towards higher water infiltration rates at 4 of the sites on all the sludge treatments, which would decrease the potential for surface runoff and the soil’s susceptibility to water erosion and associated sediment losses. There were also indications at several of the sites that the sludge additions had increased soil porosity and strength. On the lightest textured soil at ADAS Gleadthorpe, topsoil available water capacity (AWC) was increased by all the sludge types, with the AWC measurements increasing in order with OM addition rates.

The value of sewage sludge as a source of major plant nutrients was confirmed by soil total N increases at most sites, increasing long-term crop available N supply through the mineralisation of soil organic N reserves. There were also increases in soil extractable P, total and extractable S and extractable Mg concentrations at some sites. Sewage sludge was also shown to contain useful quantities of a number of minor nutrients and trace elements (e.g.

copper boron, cobalt, selenium and iodine). Liquid digested sludge applications increased grass P, Ca, Mg and Na concentrations, demonstrating that repeated sludge additions can produce grass with increased nutritional quality compared with an inorganic fertiliser control (Nicholson and Chambers, 2000).

A novel approach to soil quality assessment was pioneered at IGER in research funded by the EA (Scholefield and Witty, 2004). The measured respiratory quotient (RQ:- ratio CO_2 produced/O_2 consumed) at a given level of soil porosity was used to define the quality of a soil by its position on a 'response surface'. As the soil becomes increasingly anaerobic and quality deteriorates, the RQ increases and reduced gases are emitted (NOx, NH_3, H_2S and CH_4). The approach used a purpose-built apparatus in which gaseous emissions were pumped from an enclosure placed on the ground to a measurement head containing calibrated sensors. This one year project assessed the impcats of sewage sludge cake applications to grassland. Sewage sludge cake applications decreased soil porosity and increased soil water content - effects that were still apparent after 30 days. There was also an immediate reduction in CO_2 emissions, which was most likely due to the high lime content of the cake, with longer-term CO_2 emissions (30 days) reduced by *c.*30% compared with the no-sludge control. The work indicated that the application of high rates of sewage sludge cake (7-30 t/ha) to grassland had a detrimental impact on soil quality that could be quantified on the conceptual RQ/porosity response surface. However the study was limited to one type of sludge over a short time period, so effects on long-term soil quality and resilience could not be quantified.

3.9. Other issues

Odour emitted during and after the land spreading of sewage sludge can be a serious issue. For example, an Anglian Water funded study showed that a new sludge injection system was effective in reducing both odours and ammonia emissions following sludge application to land (Moseley *et al*., 1998). Other research has looked at odours during sewage treatment. For example, Thames Water funded a study on reducing odours from stockpiled digested sewage sludge (Winter *et al*., 2004).

The EA funded work by WRc to update the MASTAR (Model for the Analysis of Sludge Treatment And Recycling) software tool for determining the BPEO (Best Practicable Environmental Option) for sludge management in line with recent policy and technical developments (Davis *et al*., 2002). In addition, UKWIR have funded a study comparing the environmental impacts of different biosolids products and their routes of disposal or re-use which aims to demonstrate that biosolids use in agriculture is safe and based on a sound understanding of the environmental implications (UKWIR report 01/SL/12/1).

4. 'Cross-over' research

In response to recommendations in the Strategy Unit report '*Waste Not, Want Not'*, Defra set up a Waste Research Team in 2003 to distribute funds for waste management research. A 3-year Waste and Resources R&D Strategy was developed which focuses on wastes covered (now or in the future) by the Waste Framework Directive (91/156/EEC) and its 'daughter' directives, including agricultural wastes and composts (Defra, 2004). This was refined in the Waste and Resources Research Programme, the aim of which is to deliver a sound evidence base for policy development, implementation, monitoring and evaluation for sustainable waste management at both the national and local levels, and effective mechanisms for dissemination of research results. The following priority areas were identified :

- Sustainable resource consumption and management:
- Systems for resource recovery
- Residual waste management
- Market development and intervention
- Social dimension
- Environment and health (risk management and impact assessment)
- Economics
- Decision support tools

Some projects have already been commissioned and expressions of interest (EOIs) have recently been invited in all 8 areas, many of which have a strong 'read across' to aspects of sewage sludge recycling to land. For example under the 2nd call (November 2005), EOIs were invited for projects in the 'Biowaste area' viz; i) to determine the long term impact of repeated applications of composts, digestates and compost like outputs (CLOs) on soil physical, chemical and biological properties, leachate characteristics and on gaseous emissions to air (WRT312) and ii) to extend characterisation of biowastes and sludges to include a broad range of organic pollutant (WRT313). Sludge recycling to land will also benefit from the outcome of a project on attitudes to the use of organic resources on land (WRT049). There is also great benefit to the Wastes and Resources R&D programme from past and present R&D on sludge recycling to land, of which the long-term sludge experiments are a noteworthy example.

The R&D Strategy also highlighted that there is currently no easy way to establish what waste and resources related research is proposed, underway or completed, which research teams are involved or where the work is being undertaken. The programme also aims to develop an up-to-date, fully informed and easily navigated website, to ensure ease of access to the full range of information. Easy access to past and present work is an issue which applies equally to sewage sludge related work, and it is suggested that any mechanism developed for wastes should include (or at least be linked to) a similar site for sewage sludge.

In addition to this comprehensive programme of research on 'other wastes', there are a number of policy related projects which encompass or are also relevant to sludge re-use in agriculture. For example, the ALOWANCE (Agricultural Land and Organic Waste – A National Capacity Estimator) project aims to quantify and locate, temporally and spatially, the national capacity of agricultural land to accept organic 'waste' streams such as farm manures, sewage sludge, industrial 'wastes' and municipal composts etc (Defra project ES0128). Clearly, not all soils or land uses are available or suitable for the recycling of organic materials, and there is increasing concern over the quantity of heavy metals applied to soils in sewage sludge, farm manures and other organic materials that can affect long-term soil fertility. Added to this are concerns over phosphorus loadings from organic materials on certain soil types where fresh additions and accumulated levels may impact on water quality, and the risks of pathogen transfer to food crops, bathing and shellfish waters. The work will provide a strategic tool for assessing the potential agricultural landbank available for recycling organic materials (including sewage sludge), which takes account of regulatory, land use and physical barriers, and 'competition' between different organic materials.

Defra is also funding research to monitor and predict nitrate levels in surface and ground waters leaving agricultural land to assess the effectiveness of NVZ Action Programmes (Defra project WT03017). Farm scale monitoring of nitrate losses is being used to further develop models to predict the effect of changes in management practices on nitrate concentrations at a catchment level, so that the most effective practices for mitigating nitrate losses can be determined. The findings of the project could have important impacts on sludge recycling to farmland within NVZs, particularly if the closed spreading periods for organic manures are widened, or farm N loading rates are decreased as part of a revised NVZ Action Programme to achieve compliance with the Nitrates Directive.

5. Summary

Since 1998, there have been more than 60 projects commissioned in England and Wales involved with sewage sludge recycling to agricultural land. Research funded by Defra, MAFF, DETR and the FSA has covered important topics such as the effects of sludge heavy metals on long-term soil fertility, the fate and behaviour of organic contaminants in sewage sludge, and pathogen losses to the water environment. UK Water Industry Research (UKWIR), which facilitates collaborative research for water operators, has led or contributed to many of these projects on the potential environmental and health impacts of sludge recycling to agriculture, as well as to research on the agronomic and soil quality benefits of sludge recyling to agricultural land. Other notable funders of UK research include the Environment Agency, EPSRC, SEERAD, WAG and SEPA, along with individual Water Operators.

During the compilation of this review it became clear that whilst individual funders usually maintained comprehensive and up-to-date lists of research projects, there was no central register of sludge related research. Also, it was not always clear who had co-funded a project, which research group had undertaken the work, what results had been produced and how they had been disseminated.

In general, the number of jointly funded projects was indicative of good communication between the funding organisations and has minimised the potential duplication of research effort. However, there have been a number of literature reviews commissioned by UK Government, UKWIR and the EU since 2000, some of which have undoubtedly covered similar ground. These reviews have all generated numerous recommendations for further research and it was not clear to what extent these were in agreement with each other, or whether the recommendations have been accepted and acted upon.

6. R&D gaps

Based on this review of recent past and ongoing research on sludge recycling to land, we have summarised broad subject areas where more research or information is considered to be needed, viz:

1. Given recent increases in sludge production, changes in products and outlets, and improvements in sludge quality, we recommend that up-to-date information on the quantities, types and quality of sludge products being applied to agricultural land is collected, with the information made widely available to all interested stakeholders. Such a survey should build upon the format of the last 'Sewage Sludge Survey' in 1996/7 (Gendebien *et al*., 1999).

2. We recommend that the 'Heavy Metal Inventory' should be updated at regular intervals to reflect changes in farming practices, 'waste' (especially sludge and compost) production and re-use practices, and the regulatory environment. This would enable the contribution of sewage sludge to total heavy metal inputs to be placed in context with other potential sources (e.g. livestock manures, industrial 'wastes' etc.).

3. There is a pressing need to continue the "Long-term Sludge Experiments" at the network of 9 sites in Britain to provide robust scientific information to ensure that heavy metal additions in sludge (and other organic materials) do not compromise soil microbial activity and long-term fertility. Moreover, the findings of these studies are of direct relevance to the application of livestock manures, composts and other organic materials containing heavy metals. It is important that a consistent approach is taken in soil protection policy to the application of heavy metals in *all* organic materials.

   The network of "Long-term Sludge Experiment" sites also provides an experimental base (with sludge cake, metal-amended liquid sludge and inorganic metal salt study sites) to evaluate the impact of Cd additions to soils on cereal grain quality. This will ensure that soil limit values for Cd are set to ensure that grain Cd concentrations do not exceed specified EU legal limits.

4. As the quantities of sludge applied to agricultural land are likely to increase further in the future, it is important to obtain more robust measurements of ammonia and nitrous oxide emissions following land spreading and during sludge treatment prior to land spreading. Present data in the "UK Ammonia Emissions Inventory" is based on little quantitative information and is not relevant to modern sludge treatment processes and the range of enhanced and conventionally treated sludge products being recycled to farmland.

5. Whilst there has been some research looking at the agronomic benefits of enhanced treated sludge products, this needs to be extended to look not only at nitrogen supply properties but also other major nutrient contents, and to conduct these studies at the field scale. Aligned with these studies, there is a requirement to quantify the medium/long term effects of sludge products on soil quality in terms of their effects on soil physico-chemical and bio-physical properties, and to assess the long-term water quality impacts of sludge recycling to agricultural land.

6. The Waste and Resources R&D Strategy highlighted that there is currently no easy way to establish what research is proposed, underway or completed, which research teams are involved or where the work is being undertaken. This also applies equally to sewage sludge related work. The website developed for ‘wastes’ work should include (or at least be linked to) a similar site for sewage sludge.

7. Holistically, there is a need to consider how to minimise contaminant levels (e.g. heavy metals, organic contaminants) at source to improve the quality of sludges and thereby sustain the agricultural recycling route.

Publications in refereed journals

A list of scientific publications which are identified as part of this review and arose directly from DETR, MAFF and Defra funded work since 1998 is provided below.

Bhogal, A., Nicholson, F. A., Chambers, B. J. and Shepherd, M. (2003). Effects of past sewage sludge additions on heavy metal availability in light textured soils : implications for crop yields and metal uptakes. *Environmental Pollution* 121, 413-423

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Chaudri, A., Mcgrath, S., Gibbs, P, Chambers, B, Carlton-Smith C., Godley A, Bacon J, Campbell C and Aitken M. (in press). Cadmium availability to wheat grain in soil treated with sewage sludge or metal salts. *Journal of Environmental Toxicology and Chemistry*

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Gibbs, P.A., Chambers, B.J., Chaudri, A.M., McGrath, S,P. and Carlton-Smith, C.H. (2006) Initial results from long-term field studies at three sites on the effects of heavy metal-amended liquid sludges on soil microbial activity. *Soil Use and Management* (In press)

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Hill, J., Stark, B. A., Wilkinson, J. M., Curran, M. K., Lean, I. J., Hall, J. E. and Livesey, C. T. (1998). Accumulation of potentially toxic elements by sheep given diets containing soil and sewage sludge. 2. Effect of ingestion of soils treated historically with sewage sludge. *Animal Science*, 67, 87-96.

Holm, P. E., Christensen, T. H., Lorenz, S. E., Hamon, E. E., Dominigues, H. C. , Sequiera, E. M. and McGrath, S. P. (1998) Measured soil water concentrations of cadmium and zinc and estimated leaching outflows from contaminated soils. *Water, Air and Soil Pollution* 102, 105-115.

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Note that book chapters, conference proceedings, project reports etc. have not been included in this list.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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Appendix I : List of projects by topic area

Topic area	Funders	Project code	Project Title	Start date	End date	Contractors
Review	DETR, DoH, MAFF, UKWIR	SP0122	Review of the scientific evidence relating to the controls on the agricultural use of sewage sludge	1996	1998	WRC
	DETR	DETR 4896/3	Review of the Soil Metal Limits Proposed in the Draft Revision (ENV.E.3/LM) of the Sludge Use in Agriculture Directive 86/278/EEC		2000	WRC
	DETR	DETR 4907/1	Review of the Draft Revision of the Sludge Use in Agriculture Directive 86/278/EEC : Assessment of Sludge Quality		2000	WRC
	DETR		Organic contaminants in sewage sludges : A Survey of UK Samples and a consideration of their significance		2000	Lancaster University
	UKWIR	02/SL/04/2	Organic Contaminants in sewage sludge applied to agricultural land	2001	2002	Lancaster University
	Defra	WT04004	Horizontal Standards for Implementation of EU Directives on Sludge, Soil and Treated Biowaste	2002	2006	WRC
Sludge use	EA	P2-065	UK Sewage Sludge Survey		1999	WRC
Heavy metals : Sources	MAFF	OC09325/ SP0127	The vulnerability of soils to pollution by heavy metals	1995	1998	Reading University/ WRc/ADAS
	Defra	SP0516	Heavy metal content of animal manures and implications for soil fertility	2001	2002	ADAS
	Defra	SP0547	Sources and impacts of past, current and future contamination of soil	2005	2006	ADAS/JBA/Imperial College
Heavy metals : Crop response	MAFF	SP0117	Effect of heavy metals from sewage sludge on the growth and yield of legumes (Previously SP0101 and SP0110)	1982	1998	ADAS
Heavy metals : Soil microbiology	MAFF/DETR, UKWIR, WAG, (SEERAD)	SP0105/ SP0109/ SP0111	Effects of sewage sludge on agricultural productivity and soil fertility (Long-term sludge experiments - Phase I)	1994	1998	ADAS/Rothamsted/WRc
	MAFF/DETR, UKWIR, WAG, (SEERAD)	SP0114	Effects of inorganic metal salt additions to agricultural soils on soil microbial activity and long-term fertility (Long-term sludge experiments - Phase I)	1995	1998	ADAS/Rothamsted/WRc
	MAFF	SP0120	Impacts of heavy metals on soil quality with respect to microbial activity and production of crops	1997	2000	Rothamsted

Topic area	Funders	Project code	Project Title	Start date	End date	Contractors
Heavy metals : Soil microbiology	MAFF	SP0128	Effects of historic sewage sludge additions on soil heavy metal availability and biological processes	1997	2001	ADAS
	Defra/MAFF/DETR, UKWIR, WAG, EA (SEERAD)	SP0125/SP0131 /WT04001/ WT04002	Effects of sewage sludge on agricultural productivity and soil fertility (Long-term sludge experiments - Phase II)	1998	2002	ADAS/Rothamsted/WRc
	Defra/MAFF/DETR, UKWIR, WAG, EA (SEERAD)	SP0126	Effects of inorganic metal salt additions to agricultural soils on soil microbial activity and long-term fertility (Long-term sludge experiments - Phase II)	1998	2002	ADAS/Rothamsted/WRc
	Defra/MAFF/DETR, UKWIR, WAG, EA (SEERAD)	SP0130/ WT04005	Effects of sewage sludge on agricultural productivity and soil fertility (Long-term sludge experiments - Phase III)	2002	2006	ADAS/Rothamsted/WRc
	Defra/MAFF/DETR, UKWIR, WAG, EA (SEERAD)	SP0133	Effects of inorganic metal salt additions to agricultural soils on soil microbial activity and long-term fertility (Long-term sludge experiments - Phase III)	2002	2006	ADAS/Rothamsted/WRc
Heavy metals : livestock	MAFF	SP0107	Accumulation of PTEs by livestock grazed sludged grassland		1997	Chalcombe Agricultural Resources
	FSA	FS2179	Transfer of heavy metals from feeding stuffs and environmental sources into meat, milk and other foods of animal origin		1998	ITE
Organic contaminants	MAFF	SP0103	To investigate uptake of organic contaminants from sewage sludge		1995	Rothamsted
	MAFF	SP0116	Interlaboratory method performance assessment of measurement of PCDDs and PCDFs in sewage sludge		1995	CSL
	UKWIR	96/SL/03/1	Identification of priority organic contaminants in sewage sludge		1996	Lancaster University
	MAFF	SP0113	Organic contaminants from sewage sludge (Previously SP0103)		1997	Rothamsted
	UKWIR	97/SL/04/1	Pentachlorophenol (PCP) and chloranil as sources of PCDD/Fs to sewage sludge and sludge amended agricultural soils		1997	Lancaster University
	MAFF	FS2176	Organic contaminants in sewage sludge amended soils. Further studies of their environmental and food safety….	1996	1999	Lancaster University
	FSA	C01001	Simple methods to reduce potential transfer of organic chemical residues from sewage sludge amended soils to food crops	1997	2000	Wye College

Topic area	Funders	Project code	Project Title	Start date	End date	Contractors
Organic	UKWIR	01/TX/04/4	Oestrogen steroid conjugates Stability in Waste Water Streams		2001	
contaminants	UKWIR	01/TX/04/3	QSAR studies of fate and behaviour of steroid endocrines in sewage treatment		2001	
	UKWIR	01/TX/04/2	The sorptive behaviour of steroid oestrogens in sewage treatment plants		2001	
	UKWIR	01/SL/03/4	Survey of PCDD/Fs and non ortho PCBs in UK sewage sludge		2001	
	UKWIR	03/SL/04/3	Polynuclear aromatic hydrocarbons in sewage sludge amended soil-crop systems	2002	2003	
	UKWIR	04/TX/04/8	Endocrine disruptors in sewage sludge : a comparison of analytical methods		2004	
	FSA	C01029	Uptake of alkylphenols by crops following agricultural use of sewage sludge	2000	2004	Imperial College
	UKWIR	TX/04	Endocrine disrupting substances	2005		
	FSA	FS2150	Organic environmental contaminants in sludge-amended soils		1998	Lancaster University
	FSA	FS2151	Mass balance and distribution studies of PCBs and other organochlorines in grazing animals		1998	Lancaster University
Pathogens	UKWIR	98/SL/06/02	Review and status of current methods for the detection of verocytotoxic Escherichia coli, Salmonella enteriditis……..		1998	CAMR
	UKWIR	99/SL/06/3	A survey of *E. coli* in UK sludges	1998	1999	Hyder Utilities
	UKWIR	99/SL/06/4	E. coli in UK mesophically anaerobically digested sludges		1999	Hyder Utilities
	UKWIR	00/SL/06/5	Methods for the detection and enumeration of pathogens in biosolids		2000	CAMR
	UKWIR	03/SL/06/7	Pathogens in biosolids - microbiological risk assessment	2000	2003	WRC
	UKWIR	02/SL/06/6	Pathogens in biosolids - the fate of pathogens in sewage treatment		2002	Leeds University, Aqua Environment, CAMR, ADAS, University of Southampton, Thames Water, W S Atkins
	UKWIR	SL/06	Fate of pathogens following biosolids applications to soil under varying conditions (Contribution to Imperial College project)	2003		Imperial College
Radionuclides	EA	SC020150	Transfer of Radionuclides into Sewage Sludge	2005	2007	Enviros Aspinwall & Co.

Topic area	Funders	Project code	Project Title	Start date	End date	Contractors
Phosphorus	UKWIR	95/SL/02/1	The Significance of Sewage Sludge as a Source of Phosphorus Loss from Agricultural Land to Surface Waters : A Literature Review		1995	ADAS
	UKWIR	00/SL/02/5	The Environmental Impact of Phosphorus from the Agricultural Disposal of Sewage Sludge - Final		2000	ADAS
	UKWIR	05/SL/02/6	Application of Phosphorus in Industrial Biosolids Applied to Agricultural Soils - Review		2005	
	Defra, UKWIR, EA	PE0208	Development of operational guidelines to support safe application of industrial biosolids to agricultural land based on a P loss risk index	2003	2006	ADAS
	EPSRC	GR/N26074	Strategic Management of Non-Point Source Pollution from Sewage Sludge (SEAL)		2005	Lancaster, Sheffield, Reading, Newcastle Universities
Nitrogen	Defra/MAFF	CC0256	N2O losses following application of organic (sewage sludge & animal manure) and inorganic fertilisers to winter wheat	2001	2002	ADAS
Fertiliser value	UKWIR	97/SL/06/1	The content and fertiliser value of sulphur and magnesium in sewage sludge		1997	ADAS, WRC
Soil quality	UKWIR	99/SL/08/1	Beneficial effects of biosolids on soil quality and fertility. Literature review		1999	ADAS, WRC
	UKWIR	01/SL/08/2	Beneficial effects of biosolids on soil quality and fertility.	1998	2000	ADAS
	EA		Field Sensor for Soil Biological Quality	2002	2005	IGER
Other	EA		Collaborative Project to Update a Tool to Determine BPEO for Sludge Management	2003	2003	WRC
	UKWIR	01/SL/12/1	Comparative environmental aspects of available biosolids routes		2001	
Various	EA	SC980007	Recovery and Disposal of Sewage Sludge into the 21st Century (Contribution to Imperial College projects ??)	1998	2006	Severn Trent Water/UKWIR
	UKWIR, Defra, EPSRC, Water companies	WT04006	Enteric pathogen survival and nutrient transformations in sewage-sludge amended soil	2005	2007	Imperial College
	EPSRC, EA, Water companies		Predicting the agricultural benefit of novel biosolids products	2000	2004	Imperial College

Appendix II : Project summaries

The following section contains one-page summaries of the MAFF, DETR, Defra and UKWIR projects reviewed in this study. Summaries of some projects sponsored by other funders (e.g. EA, EPSRC) have also been included where appropriate.

Where the information was available, the objectives together with the main results and conclusions of the project have been provided. For other projects, only an abstract could be obtained.

Funder(s): DETR, MAFF, DoH, UKWIR

Project code: SP0122

Project title: REVIEW OF THE SCIENTIFIC EVIDENCE RELATING TO THE CONTROLS ON THE AGRICULTURAL USE OF SEWAGE SLUDGE

Contractor(s): WRc

Start date: April 1996 **End date:** March 1998 **Duration:** 2 years

Primary objectives

To review the scientific basis of the 1989 DoE Code of Practice for Agricultural Use of Sewage Sludge (Part 1), and to review the evidence since 1989 for the controls on the agricultural use of sewage sludge (Part 2).

Summary of results and conclusions

The scientific evidence underlying the 1989 Code of Practice in relation to pathogens, potentially toxic elements (PTEs), and persistent organic compounds was found to be extensive and more than 200 references were cited.

Part 2 of the report addressed the question of whether the controls in Code of Practice provided an adequate guarantee of microbiological and toxicological safety sufficient to satisfy the increased environmental expectations of the 1990's and beyond, and hence to sustain the practice of recycling sludge to agricultural land. A number of recommendations were made to strengthen the microbiological safety of sludge recycling to agricultural land. The report concluded that the available scientific evidence suggested that the soil limit values for most heavy metals specified in the Sludge Use in Agriculture Regulations were sufficient (and for some metals highly precautionary) to protect soils and crops. The on-going research on the long-term effects of heavy metals on soil microbial activity, which commenced in 1994, was thought appropriate to address the outstanding issues on this topic. However, additional research was necessary to answer questions relating to the uptake of cadmium (Cd) and lead (Pb) in livestock diets, which had been found to accumulate in the offal and under extreme conditions could exceed limit values. In terms of organic contaminants (OCs), the report concluded that the consensus international view remained that limits for OCs in sludge recycled to agriculture were not necessary, although it was recommended that the half-lives of selected OCs in sludge treated soils should be determined.

Funder(s): DETR

Project code: DETR report no : DETR 4896/3

Project title: REVIEW OF THE SOIL METAL LIMITS PROPOSED IN THE DRAFT REVISION (ENV.E.3/LM) OF THE SLUDGE USE IN AGRICULTURE DIRECTIVE 86/278/EEC

Contractor(s): WRc

Start date: **End date:** October 2000 **Duration:**

Primary objectives

To provide a concise review of the soil metal limits in the EC working document on sludge draft revision (second draft 12th January 2000, ENV.E.3/LM) which forms the basis for the revision of Directive 86/278/EEC. To draw on UK and EC research and evaluate for each metal the limit value that will protect long-term soil fertility, plant, animal and human health.

Summary of results and conclusions

The review took the approach that soil metal limits should account for both risk assessment based on scientific research findings, and the application of the precautionary principle. The review was based on the scientific evidence summarised in previous reviews. It suggested that there should be a single figure metal limit for soils in the pH range 5-7, and that sludge should not be applied to soils of pH<5. Higher soil metal limits could safely be set for soils of pH>7 containing at least 5% calcium carbonate.

Funder(s): DETR

Project code: DETR report no : DETR 4907/1

Project title: REVIEW OF THE DRAFT REVISION OF THE SLUDGE USE IN AGRICULTURE DIRECTIVE 86/278/EEC : ASSESSMENT OF SLUDGE QUALITY

Contractor(s): WRc

Start date: **End date:** October 2000 **Duration:**

Primary objectives

To assess how sludge quality criteria might be used in conforming to limit values for heavy metals in sludge.

Summary of results and conclusions

The reports focussed on the likely impact of proposed single limits for each heavy metal on UK sludge to agriculture and discussed the application of such limits in the context of sampling frequency and metal distribution within a treatment works. The assessment was based on average annual metal quality available from the most recent UK Sewage Sludge Survey for 1996/7. The report concluded that applying the proposed limits would severely restrict the amounts of sewage sludge recycled to land in the UK unless a rapid improvement in sludge quality and sampling methods occurred. In particular the Cu limit stood out as strict and an increase to 1500 mg/kg dm would bring it in line with the other heavy metals.

In order to introduce annual sampling frequencies into the regulations and utilise these data in a sensible manner it is recommended in the draft revision that limits be complied using a 90-percentile approach. This could be achieved using a compliance table which would indicate the number of allowable values above the limit in order to comply with a 90-percentil standard.

It is in the interest of sludge producers to reduce metal levels in sludge as much as possible in order to achieve improved product quality and to secure the sustainability of the agricultural outlet. Much of the copper and zinc input to sludge is of diffuse or domestic origin which cannot easily be excluded from wastewater.

Funder(s): DETR

Project code:

Project title: ORGANIC CONTAMINANTS IN SEWAGE SLUDGES : A SURVEY OF UK SAMPLES AND A CONSIDERATION OF THEIR SIGNIFICANCE

Contractor(s): Lancaster University

Start date: **End date:** December 2000 **Duration:**

Primary objectives

- To conduct a survey for a range of organic contaminants in UK sewage sludges.
- To compile relevant data for these compound classes and other compounds which may be relevant to the Working Draft
- To comment on the levels found, their relationship to the proposed standard and their significance
- To provide a considered assessment of the need for and workability of standards for organic contaminants in sewage sludge

Summary of results and conclusions

This study concluded that the introduction of limits values would have very serious implication for recycling of sewage sludge to agricultural land as virtually all European sludge would be likely to exceed the proposed limits. There was found to be little agreement in Europe as to whether controls on organic contaminants in sludge were needed, and if so which ones to regulate. The report highlighted that there were still fundamental questions about the scientific justification for such standards, the practicality of monitoring given the available analytical techniques, and whether any environmental benefits would result from imposing them.

Funder(s): UKWIR

Project code: Report No : 02/SL/04/2

Project title: ORGANIC CONTAMINANTS IN SEWAGE SLUDGE APPLIED TO AGRICULTURAL LAND

Contractor(s): Lancaster University

Start date: 2001 **End date:** 2002 **Duration:**

Primary objectives

- To undertake a critical evaluation of the proposed EU limit values, to explain how an why the standards have been derived, whether they are scientifically defensible and the practical implications of trying to implement them
- To develop the concept of 'carrying capacity', to derive carrying capacity loading rates for a illustrative range of compounds and to consider the implications of these calculations for the sustainable management of sludge amended soils
- To develop and carry out a tiered screening exercise on the compounds with proposed EU limits and to identify which are the 'priority compounds'

Summary of results and conclusions

The study concluded that the majority of sewage sludge would exceed the proposed limit values for LAS, NPE, PAHs and DEHP but that since these compounds do not accumulate in soils (LAS, NPE, DEHP) or the terrestrial food chain (PAHs) the proposed limits were difficult to justify scientifically. Whilst the majority of sludge would not exceed the proposed limits for PCBs or PCDD/Fs, the screening system developed during the study identified these as priority pollutants. The carrying capacity exercise showed that different sludge application scenarios, background soil levels and half-lives all had a marked effect on the rate of accumulation of persistent compounds in soil, although a preliminary assessment found that at current application rates some compounds would not accumulate in soil. The study recommended that new compounds identified in sludge (e.g. polybrominated flame retardants) should be evaluated to asses their half life in soil and accumulation in the food chain, and that further work was need to improve our knowledge of the effects of sewage sludge on the behaviour of organic compounds in soil.

Funder(s): Defra

Project code: WT04004

Project title: HORIZONTAL STANDARDS FOR IMPLEMENTATION OF EU DIRECTIVES ON SLUDGE, SOIL AND TREATED BIOWASTE

Contractor(s): WRc

Start date: 01/04/2002 **End date:** 31/03/2006 **Duration:** 4 years

Primary objectives

The objective of this project is to develop horizontal and harmonised European analytical standards for the measurement of a suite of inorganic and organic compounds and a range of microbial indicator organisms and pathogens that can be applied to complex organic media such as sludge, soil, and treated biowastes. Part one of the work will focus on co-normative development of horizontal standards taking as a starting point the existing analytical methodologies developed independently for sludge, soil and treated biowaste. Part two of the work will focus on the pre-normative research required to develop standards for those substances and micro-organisms considered a priority by Member States for the analysis of complex organic media such as sludge, soil and biowastes.

Summary of results and conclusions

Project on-going

Funder(s): EA

Project code: P2-065

Project title: UK SEWAGE SLUDGE SURVEY

Contractor(s): WRc

Start date: **End date:** 1999 **Duration:**

Primary objectives

- To undertake a UK survey of sewage sludge production, treatment and disposal for the year 1996/7.
- To present the results on national and regional basis.

Summary of results and conclusions

Key findings included :

- Around 47% (526,000 tonnes dry solids - tds) of sludge produced was recycled to agricultural land in the UK.
- Total UK sludge production was predicted to increase from 1,120,000 t ds in 1996/7 to 1,470,000 by 2005/6 (a 30% increase), with most of the additional amount expected to be applied to agricultural land or incinerated.
- Around 21% of sludge used in agriculture was untreated, with mesophilic anaerobic digestion (MAD) being the most widely used treatment process.
- Concentrations of potentially toxic elements (PTEs) or heavy metals in sludge were comparable to the previous survey in 1990/1, although the mean zinc concentration had reduced by 14%.
- Sludge was applied to about 80,000 ha of land or *c.* 5% of the UK agricultural land area, mostly by subsurface soil injection Average application rates were 3.5 tds/ha to arable land and 2.8 tds to grassland. Most soils had a pH greater than 6.0 and PTE concentrations close to background levels.

Funder(s): MAFF

Project code: OC09324/SP0127

Project title: THE VULNERABILITY OF SOILS TO POLLUTION BY HEAVY METALS

Contractor(s): Reading University, WRc, ADAS

Start date: 1995 **End date:** 1998 **Duration:** 4 years

Primary objectives

An integrated programme of research into the vulnerability of UK soils to pollution by heavy metals including : As, Cd, Cr, Cu, Hg, Ni, Pb and Zn. In detail the objectives were :
To compile an inventory of heavy metal inputs/loadings to soils from livestock manures, fertilisers, lime, agrochemicals, composts, irrigation water, industrial wastes and atmospheric deposition.
To set up replicated field experiments to evaluate the effects of soil pH on the uptake of heavy metals by ryegrass, and on the size and respiration of the microbial biomass
To investigate the form and bioavailability of metals in agricultural soils of different types at a range of representative sites to determine the key parameters influencing the environmental activity of metals in soil
To use GIS and statistical techniques to combine data from the inventory of heavy metals with environmental activity parameters for the metals to produce soil vulnerability maps.

Summary of results and conclusions

The inventory of soil heavy metal inputs and loadings showed that sewage sludge, livestock manures and industrial wastes were major sources of metals to agricultural soils, but not all farm fields received these materials. Atmospheric deposition was monitored at 35 sites and found to be an important source of metals to the whole of England and Wales (including non-agricultural land). However soils close to major industrial sources of metal pollution and urban areas would receive larger amounts of metals from atmospheric depositions which in some cases may be greater than other inputs. Fertilisers and lime were important sources of Cd and Cr, but less important for other metals.

Input/offtake calculations showed that all 8 metals had positive fluxes and are gradually accumulating in agricultural soils. Sewage sludge loadings were excluded from the flux calculations because <1% of agricultural land receives sludge in any year. However where sewage sludge is applied to land the accumulation of most metals would increase relative to local unsludged sites. Industrial wastes were also excluded from the flux calculations due to a lack of information on where they were applied, although they can be relatively rich source sof Zn, Cu and Cr.

The field experiments showed that metal bioavailability (uptake by ryegrass) was inversely related to soil pH but there was no evidence of phytotoxicity. This was supported by the finding from the soil physico-chemical investigations carried out on 36 soils representing about 35% of the soil mapping units in England and Wales. Increased soil acidification had a significant adverse affect on micro-organisms that was independent of soil Zn concentration.

Funder(s): Defra

Project code: SP0516

Project title: HEAVY METAL CONTENT OF ANIMAL MANURES AND IMPLICATIONS FOR SOIL FERTILITY

Contractor(s): ADAS

Start date: 1/7/2001 **End date:** 30/6/2002 **Duration:** 1 year

Primary objectives

The overall objective of the project was to provide an up-to-date overview of the trace element requirements of pigs, poultry and cattle, in order to establish the minimum dietary trace element contents and recommended allowance values necessary to maintain animal performance and meet welfare needs. An update of the heavy metal inventory was also undertaken.

Summary of results and conclusions

These results indicate that reducing Zn and Cu supplementation in livestock feeds could substantially reduce manure Zn and Cu concentrations, and hence decrease total inputs to agricultural land and loadings to individual fields. This would be an effective method of protecting soils from the long-term accumulation of heavy metals. However, it is widely recognised that metal bioavailability and especially uptake by plants, varies considerably depending on the form of the metal entering the soil, soil physico-chemical conditions and the genotype of the crop plant. Thus, the impact of the metal inputs to the soil will vary between sites, and with soil and crop growth conditions.

A decision on whether and by how much to reduce dietary Zn and Cu supplementation should be based on an objective assessment of all the environmental, economic and animal welfare issues compared with the impacts of alternative approaches available for animal production.

Funder(s): Defra

Project code: SP0547

Project title: SOURCES AND IMPACTS OF PAST, CURRENT AND FUTURE CONTAMINATION OF SOIL

Contractor(s): A DAS, WRc, JBA Consulting

Start date: 01/03/05 **End date:** 30/11/05 **Duration:** 9 months

Primary objectives

The overall objective of this project was to identify the major past, current and future sources of soil contaminants, and to assess their potential impacts on soil functions. More specifically, the objectives of the project were:

- To identify the major contaminants applied or deposited on soils.
- To identify the most important current and future sources of soil contaminants and assess their relative significance.
- To assess the potential for contaminant mobilisation and transportation by floodwaters or other mechanisms.
- Review current and planned regulations and voluntary initiatives to control contaminant sources, and assess their actual and potential effectiveness.
- Assess the relative impact of each contaminant and source on soil functions, and any associated economic implications.
- Identify and prioritise knowledge deficiencies and research needs with respect to the significance and impacts of contaminant inputs to soil.

Summary of results and conclusions

A quantitative inventory of heavy metal inputs showed that agricultural soils were most at risk from heavy metal accumulation through the application of livestock manures (in particular pig and poultry manures), sewage sludge, composts and paper sludge. Hence, it may be appropriate to consider the introduction of maximum permissible soil metal concentrations to protect agricultural land from long-term heavy metal accumulation for all organic manure additions to soils (similar to the controls currently in place for sewage sludge applications), unless strategies can be found to further reduce their metal content.

Action taken during the 1980s and 1990s to curb emissions have led to significant reductions in POP concentrations in sewage sludge, with the existing body of scientific evidence suggesting that there are no significant environmental impacts from these compounds where sludge is applied to agricultural land.

Some liquid discharges of radionuclides are authorised into the sewer system, with the land application of sewage sludge a potential pathway for radionuclides to enter soil. However, the body of research evidence indicates that the effect on soil radionuclide concentrations is likely to be undetectable.

Routes by which pathogens may enter the human food chain include the application of organic manures (e.g. livestock manures, sewage sludge, livestock excreta deposition directly in the field) and the use of water in food crop production. Because of the large quantities involved, the prevalence of pathogens and the relative lack of controls (either legislative or voluntary), the application of livestock manures/excreta to agricultural land is currently the most important single source of enteric pathogens to soils

Funder(s): MAFF

Project code: SP0117

Project title: EFFECT OF HEAVY METALS FROM SEWAGE SLUDGE ON THE GROWTH AND YIELD OF LEGUMES (PREVIOUSLY SP0101 and SP0110)

Contractor(s): ADAS

Start date: 1991 **End date:** 1998 **Duration:** 7 years

Primary objectives

To evaluate the effect of heavy metal additions in sewage sludge on the growth and yield of legumes and other arable crops

Summary of results and conclusions

The effect of heavy metal additions in past sewage sludge applications on soil metal availability and the growth and yield of crops was evaluated at two sites in the UK. At Gleadthorpe, sewage sludges enriched with salts of zinc (Zn), copper (Cu) and nickel (Ni) had been applied to a loamy sand in 1982 and 1986. At Rosemaund, sewage sludges naturally contaminated with Zn, Cu, Ni and chromium (Cr) had been applied from 1968-1971 to a sandy loam. From 1994 to 1997, the yields of both cereals and legumes at Gleadthorpe were up to 3 t/ha lower than the no-sludge control where total topsoil Zn and Cu concentrations exceeded 200 mg/kg and 120 mg/kg, respectively, but only when topsoil ammonium nitrate extractable metal levels also exceeded 40 mg/kg Zn and 0.9 mg/kg Cu. At Rosemaund, yields were only decreased where total topsoil Cu concentrations exceeded 220 mg/kg or 0.7 mg/kg ammonium nitrate extractable Cu. These results demonstrate the importance of measuring extractable as well as total heavy metal concentrations in topsoils when assessing likely effects on plant yields and metal uptakes, and setting soil quality criteria.

Funder(s): MAFF

Project code: SP0120

Project title: IMPACTS OF HEAVY METALS ON SOIL QUALITY WITH RESPECT TO MICROBIAL ACTIVITY AND PRODUCTION OF CROPS

Contractor: IACR- Rothamsted

Start date: 01/04/97 **End date**: 31/03/00 **Duration**: 4 years

Primary objectives

The scientific objectives of the project were to determine which concentrations of metals in soil adversely affect soil populations and activities of soil microbes by measuring (i) effects on pea /bean rhizobia, (ii) ability of the soil microbial biomass to utilise specific carbon sources, and (iii) the genetic diversity of important soil bacteria.

Summary of results and conclusions

The project showed that *R. leguminosarum* biovar *viciae* was sensitive to metals, leading to effects at soil concentrations of zinc greater than 200 mg/kg and copper at more than 250 mg/kg. Yields of pea in the field were reduced by 50% when soil contained zinc at more than 290 mg/kg, but copper had no significant effect on yields. The results support the lowering of the limits in 1996 to 200 mg Zn kg^{-1} soil . They also show that for Cu, the present limits are protective of the rhizobia studied but perhaps not of pea yields.

The Biolog method was shown to be rather insensitive to metals in soil derived from sewage sludge. Thus the use of Biolog for monitoring effects in moderately contaminated soils, typical of the situations relevant to sewage sludge limits, may not be as useful an indicator as it can be in more polluted soils.

The work showed that, in contrast to the single species/single function approach, a large range of bacteria in the pseudomonad group can show changes in diversity, but that this may not necessarily be in a negative direction. Some more sensitive types may have been lost, but the actual diversity measured increases with increased metal concentrations. Ecological theory says that when there is moderate stress (e.g. heavy metals) organisms may be freed to some extent from a process known as competitive exclusion. This means that when there is little stress, few 'types' can dominate, but that this effect is weakened by stress, allowing more types to come in. This seems to be the case in the sludge-treated soils studied here.

Overall, this means that single species with important ecological functions are more likely to be sensitive to change. Within larger 'community level' measurements, a large number of changes may lie hidden. As yet in the literature, no one has been able to make the link between community level measurements such as Biolog or PCR-based techniques, and functions. It is then a political decision whether to regulate on single species studies with associated loss of an important function, rather than other measurements made at the larger community scale (e.g. Biolog or diversity in this study). Use of biologically based observed effects on key sentinel species appears to be the way that the UK is guiding policy. Is recommended that soils do not have to remain at background metal concentrations during waste disposal, but that some increase is possible, with little chance of risk to important soil processes. This means that the maximum concentrations have to be chosen based on observed biological effects, such as those reported here for populations of rhizobia, and set to protect the most sensitive soils.

Funder(s): Defra/MAFF

Project code: SP0128

Project title: EFFECTS OF HISTORIC SEWAGE SLUDGE ADDITIONS ON SOIL HEAVY METAL AVAILABILITY AND BIOLOGICAL PROCESSES.

Contractor: ADAS

Start date: 01.04.97 **End date**: 31.03.01 **Duration**: 4 years

Primary objectives

To evaluate the effects of heavy metal additions in sewage sludge on soil heavy metal availability, nitrogen mineralisation and soil microbial activity.

Summary of results and conclusions

This work undertaken at the historic sludge experimental sites at ADAS Gleadthorpe and Rosemaund emphasised the importance of measuring extractable soil heavy metal concentrations in addition to total concentrations when assessing metal bioavailability, particularly when comparing the effect of different sludges and soil types. Measurements undertaken between 1994 and 2000 showed no consistent changes in topsoil ammonium nitrate extractable metal (Zn, Cu, Ni and Cd) concentrations, which suggested that the soil metal concentrations at these sites were in equilibrium with the soil. The metal (Zn & Cu) availabilities at Rosemaund were similar to sites which had a history of sludge additions, whereas those at Gleadthorpe, were much higher than the sludge amended field soils, representing a 'worst-case scenario' situation in terms of likely heavy metal availabilities. Elevated soil heavy metal concentrations had no effect ($P>0.05$) on N mineralisation and respiration rates measured in the field at Gleadthorpe. However, at both Gleadthorpe and Rosemaund, PMN (laboratory determination) decreased ($P<0.05$) with increasing soil Cu concentrations.

Funder(s): Defra/MAFF/DETR, UKWIR, WAG, EA (SEERAD)

Project code: SP0105/SP0109/SP0111/SP0125/SP0130/SP0131/WT04001 /WT04002/WT04005

Project title: EFFECTS OF SEWAGE SLUDGE APPLICATIONS TO AGRICULTURAL SOILS ON SOIL MICROBIAL ACTIVITY AND THE IMPLICATIONS FOR AGRICULTURAL PRODUCTIVITY AND LONG-TERM SOIL FERTILITY. (LONG-TERM SLUDGE EXPERIMENTS : PHASES I-III)

Contractor: ADAS, Rothamsted Research, WRc, Macaulay Institute, SAC

Start date: 01.07.94 **End date:** 30.06.06 **Duration:** 12 years

Primary objectives

To determine the effects of sewage sludge applications to agricultural soils on soil microbial activity and the implications for agricultural productivity and long-term soil fertility.

Summary of results and conclusions

- Between 1998 and 2002, significant (P<0.05) responses in soil microbial activity and agricultural productivity were measured following the application during phase I (1994-1998) of metal rich sludge cakes and metal-amended liquid sludges. The soil samples taken in springs 1999 and 2001 from all the treatment plots at the 9 sites showed significant (P<0.05) responses in soil microbial activity, primarily on the Zn and Cu dose response treatments.
- Out of a possible 108 microbial and crop yield responses for each metal on the sludge cake treatments, 25 responses were measured for Zn (23% of total), 44 for Cu (41%) and 10 for Cd (9%), compared with 8 responses out of a possible 35 for Zn (23%), 13 for Cu (37%) and 3 for Cd (9%) on the metal-amended liquid sludge treatments.
- The four sludge cake sites with the lowest respiration rates and biomass C contents were the sites where most of the microbial responses were evident (63% of responses).
- The sludge cake sites with the highest porewater soluble Cu concentrations (Gleadthorpe and Rosemaund) showed RQ and BQ responses in both 1999 and 2001.
- Decreases in wheat grain yields were measured on the Cu (particularly) and Zn dose-response treatments at both the sludge cake and metal-amended liquid sludge sites.
- The average amount of applied sludge C remaining in the topsoil horizon in 2001 across the nine sites was estimated at 45% and 27% for the digested and raw sludge cakes, respectively.
- Ammonium nitrate extractable Zn and Cd concentrations were generally higher at the liquid sludge compared with the corresponding sludge cake sites. In contrast, extractable Cu concentrations were higher on the cake than the liquid sludge treatments.

Although statistically significant responses were apparent, and the body of evidence is growing, the interim results indicate no consistent metal effects on microbial activity that could unequivocally be attributed to metal toxicity *per se*. Further soil sampling and measurements during phase III of this long-term study (SP0130) will help to establish whether the effects measured so far are true and consistent.

Funder(s): Defra/MAFF/DETR, UKWIR, WAG, EA (SEERAD)

Project code: SP0114/SP0126/SP0133

Project title: EFFECTS OF INORGANIC METAL SALT ADDITIONS TO AGRICULTURAL SOILS ON SOIL MICROBIAL ACTIVITY AND LONG-TERM SOIL FERTILITY. (LONG-TERM SLUDGE EXPERIMENTS : PHASES I-III)

Contractor: ADAS, Rothamsted Research, WRc

Start date: 01.07.94 **End date:** 30.06.06 **Duration:** 12 years

Primary objectives

To determine the effects of established heavy metal concentrations on soil microbial activity and the implications for agricultural productivity and long-term soil fertility.

Summary of results and conclusions

- The established soil heavy metal concentrations following the application during phase I (1994-1998) of metal carbonates resulted in significant ($P < 0.05$) responses in soil microbial activity and agricultural productivity.
- Out of a possible 35 microbial and crop yield responses for each metal, six (17% of total) were measured for Zn, 14 for Cu (40%) and three for Cd (9%).
- Soil extractable Zn and Cd concentrations were generally *lower* on the metal salt experiments compared with the corresponding sludge cake and metal-amended liquid sludge experiments.
- Soil extractable Cu concentrations were *intermediate* between the corresponding sludge cake (highest) and metal-amended liquid sludge (lowest) experiments.

Although statistically significant responses were apparent, and the body of evidence is growing, consistent metal effects on microbial activity and crop productivity have not been found. Further soil sampling and measurements during phase III of this long-term study (SP0133) will help to establish whether the effects measured so far are consistent and true.

Funder(s): MAFF

Project code: SO0107

Project title: ACCUMULATION OF POTENTIALLY TOXIC ELEMENTS BY LIVESTOCK GRAZING SLUDGED GRASSLAND.

Contractor: Chalcombe Agricultural Resources

Start date: 01.03.94 **End date:** 1997 **Duration:** 3 years

Primary objectives

- To provide information on the fate of PTEs consumed by livestock grazing sludged land, especially that to which sludge was applied in successive does over a number of years up to the statutory limit for soil cadmium.
- To study the effect of season and sludge application method on ingestion of herbage, soil and sludge by lambs grazed on pastures treated with a single, normal operational amount of sludge.
- To further develop a model of soil/grass/animal accumulation of PTEs.
- To confirm the margin of safety with respect to the statutory and guideline limits for PTE levels in grassland soils.

Summary of results and conclusions

To assess the extent of accumulation of PTEs by direct ingestion of soil and sewage sludge housed weaned lambs were given diets comprising dried grass and three different soils. Soil was replaced by dried digested sewage sludge at increasing levels. Voluntary DM intake was markedly depressed by the inclusion of sewage sludge in the diet but there was no effect on diet apparent digestibility. Live-weight gain was depressed by the addition of sewage sludge to the diet, with liver and kidney weights also reduced. The apparent availability coefficients for Cd, Pb and Cu increased with increasing level of sewage sludge in the diet, as did their concentrations in the liver and kidney. Concentrations of Pb in liver of lambs given the highest level of sludge approached the statutory limit set for human food. The results indicated that in relation to accumulation of PTEs in liver and kidney there would appear to be little margin of safety with respect to the current United Kingdom statutory limits for the concentrations of Cd and Pb in sludge-amended soils.

To assess the possible accumulation of PTEs from soils treated historically with sewage sludge, housed weaned lambs were given either dried grass as a sole food (grass control), or diets comprising dried grass and soil from two experimental sites, plots within which had been treated 14 years previously with different quantities of sewage sludge. Soils from the two sites had contrasting physical characteristics, pH and contents of calcium. Plots at each site had a range of concentrations of cadmium (Cd) in the soil up to three times the United Kingdom (UK) statutory limit of 3 mg Cd per kg DM. Voluntary DM intake was not affected significantly by any dietary treatment. Cd and Pb concentrations in liver and kidney increased with increasing soil Cd and Pb contents. A depletion of the concentration of Cu in the liver was observed in all treatments containing soil in the diet. No significant accumulation of PTEs was observed in muscle tissue. It was concluded that the current UK statutory limits for the concentrations of Cd and Pb in soils treated with sewage sludge should be reviewed in the light of these results, though they require confirmation in the grazing situation.

Funder(s): EPSRC

Project code: GR/L96592/01

Project title: IN-SITU CONTAINMENT OF HEAVY METAL CONTAMINATED SOIL USING ZEOLITES CONDITIONED SEWAGE SLUDGE

Contractor: Surrey University

Start date: 17/9/98 **End date:** 16/2/02 **Duration:** 3.5 years

Abstract

The research programme investigated a novel non-invasive remediation technology for the containment of heavy metals in contaminated soils. The technique involved the use of natural zeolites conditioned sewage sludge for the immobilisation of heavy metals by physical/chemical entrapment within the zeolite complex porous structure. It is anticipated that the organic and nutrient properties of the sewage sludge combined with the valuable ion exchange properties of the natural zeolites to entrap heavy metals, will provide a unique technology for the reclamation of heavy metal contaminated soils. It is expected that the research will (1) reduce the long-term environmental effects associated with the significant extent of heavy metal-contaminated soils by developing an in-situ technology based on the use of natural resources for metal containment; (2) enable the extraction of heavy metals from sewage sludge and therefore enhance the its potential for re-use as a fertiliser to improve the nutrient qualities of the soil; (3) develop a novel non-invasive in-situ remediation technology which can be designed and engineered for a wide range of potential practical applications (remediation of metal-contaminated sites, landfill containment/treatment) in the UK in particular and Europe in general.

Funder(s): UKWIR

Project code: 96/SL/03/1

Project title: IDENTIFICATION OF PRIORITY ORGANIC CONTAMINANTS IN SEWAGE SLUDGE VOLUME 1 CONTAINING THE MAIN REPORT

Contractor: Lancaster University

Start date: **End date:** 1996 **Duration:**

Abstract

A review of the occurrence of organic compounds in sewage sludge is presented, with literature compiled on over 300 organic compounds. Likely inputs of organic contaminants to agricultural soils via sewage sludge are determined and results compared against soil quality standards. A screening approach is developed, based on compound physicochemical properties, to assess the likely behaviour and fate of chemicals introduced into agricultural soils in sewage sludge. The propensity for compounds to leach to groundwater or transfer to crop plants and grazing animals is assessed. The sludge- soil/ herbage- livestock' pathway is the most important with regard to potential human exposure of sludge- derived organics. Routine operational practice for the application of sewage sludge to land is very unlikely to result in UK soil quality limits for trace organics being exceeded. Repeated applications of sludge to pasture land may lead to the exceedence of the more stringent soil quality guidelines adopted elsewhere.

Funder(s): UKWIR

Project code: 97/SL/04/1

Project title: PENTACHLOROPHENOL (PCP) AND CHLORANIL AS SOURCES OF PCDD/ FS TO SEWAGE SLUDGE AND SLUDGE AMENDED AGRICULTURAL SOILS

Contractor: Lancaster University

Start date: **End date:** 1997 **Duration:**

Abstract

The contribution of pentachlorophenol (PCP) and chloranil- based dyes and pigments to the dioxin (PCDD/ F) content of sewage sludges and the potential for PCDD/ Fs derived from these sources to persist in sludge amended soils and to trtansfer through the agricultural food chain is discussed. Sources, production and use of PCP and chloranil are described along with regulatory issues. Where possible, UK production, use and import statistics have been updated. The application of other types of organic amendments (eg farmyard manure), paper waste sludge and textile waste could represent important sources of PCDD/ Fs to agricultural soils. At present the application of these wastes is not subject to the same level of control as sewage sludge. There is very limited data available at present to quantify their current and future impact. Using a congener- specific pathways analysis model, the addition of sludge containing high concentrations of PCDD/ F congeners associated with PCP and chloranil-based sources does n …..[abstract incomplete].

Funder(s): UKWIR

Project code: 01/TX/04/4

Project title: OESTROGEN STEROID CONJUGATES STABILITY IN WASTE WATER STREAMS

Contractor:

Start date: **End date:** 2001 **Duration:**

Abstract

A laboratory simulation of the stability of steroid conjugates in sewage on passage through a sewer and primary settlement within a sewage treatment plant, using radiolabelled (3H) materials at environmentally realistic concentrations (100 ng l-1). Oestradiol-17-glucuronide de-conjugated rapidly in the presence of a low concentration of sewage suggesting that this type of conjugate would not remain intact during transfer to, and primary settlement within, a sewage treatment plant. Oestrone-3-sulphate was more robust, giving little indication of de-conjugation over the first 4 hours. Limited studies are also reported for activated sludge addition and degradation by-products.

Funder(s): UKWIR

Project code: 01/TX/04/3

Project title: QSAR STUDIES ON FATE AND BEHAVIOUR OF STEROID ENDOCRINES IN SEWAGE TREATMENT

Contractor:

Start date: **End date:** 2001 **Duration:**

Abstract

Literature data and quantitative structure activity relationships (QSARs) were used in TOXCHEM modelling to predict the behaviour of steroid endocrine disrupters in typical U.K. sewage treatment works. Models for two typical UK sewage treatment plant configurations predicted that volatilisation during sewage treatment will be insignificant for all the oestrogens modelled resulting in a significant proportion of residues in influent sewage appearing in effluents depending on the biodegradation efficiency. It was not possible to include sludge digestion within the TOXCHEM model.

Funder(s): UKWIR

Project code: 01/TX/04/2

Project title: THE SORPTIVE BEHAVIOUR OF STEROID OESTROGENS IN SEWAGE TREATMENT PLANTS

Contractor:

Start date: **End date:** 2001 **Duration:**

Abstract

The ability of activated sludge particles to sorb steroid oestrogens was tested in the laboratory with fresh mixed liquor from an aeration tank and radio-labelled steroid oestrogen analogues. Most of the sorption was completed in the first minutes of the equilibrium. However, only ethinyloestradiol (EE2) was stable in the sewage matrix, the majority of oestradiol (E2) and oestriol (E3) were rapidly transformed. The main E2 by- product was another oestrogen, oestrone. With an ambient sludge concentration of 3.5 g/ L, only 13% of E3 (Kd 51), 30% of E2 (Kd 142) and 60% of EE2 (Kd 289) was removed by sorption.

Funder(s): UKWIR

Project code: 01/SL/03/4

Project title: SURVEY OF PCDD/Fs AND NON-ORTHO PCBs IN UK SEWAGE SLUDGES

Contractor:

Start date: **End date:** 2001 **Duration:**

Abstract

A survey of the PCDD/ F and non- ortho PCB content in the digested sludge of 14 UK wastewater treatment works was carried out. The range of total PCDD/ F concentration in the sludges was 8880- 428000 pg/ g dw. Total non- ortho PCB concentrations were in the range 272- 63000 pg/ g dw. The PCDD/ F I- TEQs of the sludges studied were comparable to those published in the literature with a range of 20- 225 pg I- TEQ/ g dw. The non- ortho PCBs usually added 3- 4 pg/ g to the total I- TEQ. The homologue group pattern of the PCDD/ Fs was consistent with that found in most sewage sludges.

Funder(s): UKWIR

Project code: 03/SL/04/3

Project title: POLYNUCLEAR AROMATIC HYDROCARBONS IN SEWAGE SLUDGE AMENDED SOIL-CROP SYSTEMS

Contractor:

Start date: **End date:** 2003 **Duration:**

Abstract

Sewage sludges can contain organic chemicals from a variety of sources at low concentrations. A previous report (02/SL/04/2) concluded that polynuclear aromatic hydrocarbons (PAHs) do not accumulate in the terrestrial foodchain and that a proposed EC limit value appears inappropriate. This report describes a study to address the issue. Worst case scenarios of sewage sludge being applied to the surface of grassland were investigated. Pot trials were also conducted with carrots and lettuce to investigate realistic or elevated sewage sludge application rates. The outcome of these studies was that typical UK sludges contain PAH concentrations above the suggested limits, precluding them from agricultural use. Evidence from this work suggests that the sludges pose no risk to the environment, animal or human health when applied under suitably controlled conditions.

Funder(s): UKWIR

Project code: 04/TX/04/8

Project title: ENDOCRINE DISRUPTERS IN SEWAGE SLUDGE: A COMPARISON OF ANALYTICAL METHODS

Contractor:

Start date: **End date:** 2004 **Duration:**

Abstract

The aim of this research was to determine the oestrogenicity of sewage sludge and soils and to determine endocrine disrupting compounds (EDCs) using a newly developed method. The results show that free steroid oestrogens were detectable at low concentrations in sewage sludge. Oestrogenicity testing of sewage sludge using the ER-CALUX bioassay showed that sewage sludge is oestrogenic. However, aqueous leachates of the soil and most of the sludge samples (except primary and activated sludge) gave no oestrogenic response. This suggests that oestrogenic compounds present in sludge may not leach into groundwater or be bio-available when applied to land.

Funder(s): FSA

Project code: C01029

Project title: UPTAKE OF ALKYLPHENOLS BY CROPS FOLLOWING AGRICULTURAL USE OF SEWAGE SLUDGE

Contractor: Imperial College

Start date: Jan 2000 **End date:** Mar 2004 **Duration:**

Objectives

The aim of this project was to examine the potential of alkylphenols and their breakdown products to enter the food chain following uptake by food crops treated with sludge.

Summary of results and conclusions

This research investigated the uptake of nonylphenols (NPs), which are potential endocrine disrupters, from sewage sludge into food crops.

Uptake of NPs from a hydroponic system was studied in broad beans, spring wheat and carrots. All three crops were found to uptake NPs to varying degrees from concentrate solution. The concentration of NPs was highest in the roots and shoots of all three crops. In soil experiments, NP was found to degrade more rapidly in a clay loam soil sample with low organic matter and low sand content, compared to three other soils examined. In lysimeter trials, an instrument designed to collect soil water, uptake of NP by crops was low compared to the hydroponic system and the concentrations showed little variation in different parts of the crops. Overall, the results are in line with previous studies and show that while NPs can enter some crops from sewage sludge, the amounts found in edible portions of the plant pose no risk for human health.

Funder(s): UKWIR

Project code: 98/SL/06/2

Project title: REVIEW AND STATUS OF CURRENT METHODS FOR THE DETECTION OF VEROCYTOTOXIC ESCHERICHIA COLI, SALMONELLA ENTERITIDIS PT4, SALMONELLA TYPHIMURIUM DT104, SHIGELLA SONNEI AND CAMPYLOBACTER JEJUNI IN TREATED AND UNTREATED BIOLOGICAL EFFLUENTS

Contractor: CAMR

Start date: **End date:** 1998 **Duration:**

Abstract

No abstract available

Funder(s): UKWIR

Project code: 99/SL/06/3

Project title: A SURVEY OF *E. COLI* IN UK SLUDGES

Contractor: Hyder Utilities

Start date: 1998 **End date:** 1999 **Duration:**

Objectives

Forthcoming regulations are expected to modify existing controls on the types of treatment and land use practices for the UK in relation to the application of sewage sludge to agricultural land. The objectives of the work were therefore to undertake a survey to :

- Establish the effectiveness of existing processes with a view to predicting which will be acceptable under the new Regulations
- To provide information which will help in establishing the extent to which expenditure is likely to be required.

Summary of results and conclusions

All of the processes surveyed reduced the numbers of *E. coli* . Composting, lime addition and thermal drying reduced *E. coli* numbers to the detection lijmit ofb the analytical method. For all these methods over 90% of the results showed bacterial reductions were log 6 or greater.
Lagooning of sludge was capable of significantly reducing numbers of *E. coli* and depending on the method of operation, reductions in the order of log 5 were achieved.
Mesophilic Anaerobic Digestion (MAD), the process carried out at the majority of sites surveyed, reduced *E. coli* numbers by, on average, between log 1.4 and 2.3 depending on the solids content of the product. 78% of all reductions for a liquid product were in the range log 1 to 2. 89% of results for a cake product were in the range log 2 to 4.
The one vermiculture site showed results intermediate between MAD and the 'advanced' treatment processes.

Project code: 99/SL/06/4

Project title: *E. COLI* IN UK MESOPHILIC ANAEROBICALLY DIGESTED SLUDGES

Contractor: Hyder Utilities

Start date: **End date:** 1999 **Duration:**

Objectives

To confirm the performance of Mesophilic Anaerobic Digestion (MAD) in reducing numbers of *E. coli* previously reported by taking 20 paired samples before and after digestion at 5 sites selected from the first survey.

Summary of results and conclusions

The results confirmed that MAD can reduce numbers of *E. coli* by up to 4 orders of magnitude. The average log reduction recorded was 2.08, higher than observed in the first survey. 92% of reductions were 2 or greater, compared to 76% in the first survey. This was not unexpected since the sites had been chosen as among the apparently better sites originally surveyed.
At the 5 sites, average reductions varied between 1.35 and 3.36 but there were no clear reasons for the differences.

Funder(s): UKWIR

Project code: 00/SL/06/5

Project title: METHODS FOR THE DETECTION AND ENUMERATION OF PATHOGENS IN BIOSOLIDS

Contractor: CAMR

Start date: **End date:** 2000 **Duration:**

Abstract

A generic method has been developed for the resuscitation, detection and enumeration of bacterial pathogens. This provides a robust and flexible platform for pathogens in model digester systems, and in field trials. New methods for cryptosporidia and viruses have also been developed which are also applicable to such sample types. The methods allow enumeration of the target pathogens to be performed in the presence of high background levels of microorganisms. Although the methods were devised specifically for biosolids, the techniques are applicable to wide variety of organic wastes.

Funder(s): UKWIR

Project code: 03/SL/06/7

Project title: PATHOGENS IN BIOSOLIDS - MICROBIOLOGICAL RISK ASSESSMENT

Contractor: WRc

Start date: **End date:** 2003 **Duration:**

Abstract

Biosolids represent the solid fraction of sewage and potentially contain a number of human and animal pathogens. This report describes a microbiological risk assessment to quantify the risks to humans from consumption of root crops grown on land to which treated biosolids have been applied in accordance with the Safe Sludge Matrix and the Regulations. The seven pathogens studied were Escherichia coli O157, Cryptosporidium, Giardia, Salmonella, Campylobacter, Listeria monocytogenes and enteroviruses. A number of worst-case assumptions have been made to accommodate lack of data. The predicted risks to the UK population as a whole are remote. Indeed, the highest risk is for Cryptosporidium with one infection in the UK population every 45 years on average. The model shows that the 12 month harvest interval compensates for any increased risks due to inefficient operation of sludge treatment at the works.

Funder(s): UKWIR

Project code: 02/SL/06/6

Project title: PATHOGENS IN BIOSOLIDS - THE FATE OF PATHOGENS IN SEWAGE TREATMENT

Contractor: Leeds University, Aqua Environment, CAMR, ADAS, University of Southampton, Thames Water, W S Atkins

Start date: **End date:** 2002 **Duration:**

Abstract

This study has evaluated the survival of a number of enteric pathogens added to thickened sewage sludge which was subjected to treatment by a range of processes operated under Code of Practice* conditions. These processes were: mesophilic anaerobic digestion (MAD), pasteurisation followed by MAD, lime stabilisation and composting. The experiments were carried out at bench-scale with additions of Salmonella senftenberg, S. dublin, S. enteriditis, S. typhimurium, Listeria monocytogenes, Campylobacter jejuni, Cryptosporidium parvum and poliovirus with the aim of achieving 106 organisms in the sludge. In addition the numbers of indigenous Escherichia coli were determined, not only in the bench-scale reactors but also at nominated full-scale plants that were operated under Code of Practice conditions; thermal drying was evaluated at full-scale only. Indigenous E. coli were shown to have similar survival properties to the verotoxigenic strain of E. coli O157 and could act as an indicator for this pathogen.

Funder(s): EA

Project code: SC020150

Project title: TRANSFER OF RADIONUCLIDES INTO SEWAGE SLUDGE

Contractor: Enviros Aspinwall and Co Ltd

Start date: 11/3/05 **End date:** 1/3/07 **Duration:** 2 years

Abstract

Many non-nuclear sites are authorised by the Agency to discharge radioactivity to sewer. The radionuclides may be removed with sewage sludge at a treatment works or discharged with the treated effluent to rivers. Since the late 1990s, it has not been possible for sewage sludge to be disposed of to sea and there has been an increase in disposal to land. Once on land the radionuclides may become incorporated into food products. It has shown that where the effluent from a number of disposers is treated at a single sewage treatment works, then doses to members of the public exposed to radionuclides passing out of the works in treated effluent reaching rivers and in sludges disposed to landfill can be greater than 20 microSv/y. In addition, liquid discharges from some nuclear sites pass through a sewage treatment works. However one of the significant uncertainties in the assessment of doses from disposal of sewage sludge is the partition of radionuclides between sewage sludge and treated effluent. Some partitioning data has been published and some work has been carried out by NRPB and the Food Standards Agency. This work will build on existing information to provide improved and robust data.

Funder(s): UKWIR

Project code: 95/SL/02/1

Project title: THE SIGNFICANCE OF SEWAGE SLUDGE AS A SOURCE OF PHOSPHORUS LOSS FROM AGRICULTURAL LAND TO SURFACE WATERS : A LITERATURE REVIEW

Contractor: ADAS

Start date: **End date:** 1995 **Duration:**

Abstract

Sludge applications based on nitrogen requirements may lead to an accumulation of phosphorus in soil. There is a risk of consequential eutrophication in vulnerable areas. Although the immediate availability of phosphorus from sewage sludge may be low it is considered a useful source to crops in rotations. P loss in surface and sub- surface run- off from freshly sludged land is comparable or less than that from other fertilizers, typically less than 1% of phosphorus applied. The continued land application of sludge poses only a small threat to the environment.

Funder(s): UKWIR

Project code: 00/SL/02/5

Project title: THE ENVIRONMENTAL IMPACT OF PHOSPHORUS FROM THE AGRICULTURAL USE OF SEWAGE SLUDGE - FINAL

Contractor: ADAS

Start date: 1994 **End date:** 2000 **Duration:** 6 years

Abstract

This project started in 1994 and most of the experimental work finished in 1998. Progress reports on the work have been published over the last five years. The six final reports from the individual experiments are presented here. Experiment 6, which studies the long term cycling of phosphorus when sludge is used agriculturally, is continuing through the 1999 and 2000 growing seasons and a supplementary report on this work will be issued in mid 2001. Reports presented here are

- amounts, form and bioavailability of phosphorus in sewage sludge - final report
- accumulation and migration of phosphorus in sludge amended soil - final report,
- phosphorus leaching from free-draining soils receiving sewage sludge - final report,
- phosphorus loss from drained clay soils receiving sewage sludge - final report,
- phosphorus loss in surface run-off from sludge amended soil - final report, phosphorus cycling in soils receiving sewage sludge - final report. In addition a literature review entitled 'the significance

Funder(s): UKWIR

Project code: 05/SL/02/6

Project title: APPLICATION OF PHOSPHORUS IN INDUSTRIAL BIOSOLIDS APPLIED TO AGRICULTURAL SOILS - REVIEW

Contractor:

Start date: **End date:** 2005 **Duration:**

Abstract

This report reviews biosolid phosphorus, processes of phosphorus loss from land, and the range in measures available to control the loss. The factors affecting risk of P loss from agricultural land were considered and a number of potential measures to control P loss were identified, requiring prior identification of high-risk fields for targeting of these options. Following visits to 3 water companies, a preliminary methodology for assessing the risk of phosphorus loss as a function of the risk of in-field mobilization and the risk of delivery from the field to the watercourse was developed for testing.

Funder(s): EPSRC

Project code: GR/N266074 and GR/559246/02

Project title: STRATEGIC MANAGEMENT OF NON-POINT SOURCE POLLUTION FROM SEWAGE SLUDGE

Contractor: Lancaster University, Newcastle University, Reading University, Sheffield University

Start date: **End date**: 31/12/05 **Duration**:

Primary objectives

The aim of the project is to develop an advice matrix for end-users on the most suitable form and frequency of spatially-sensitive sludge application to land to achieve sustainable sludge management and to minimise environmental risk. The specific objectives are :

- To develop an advice matrix for end-users to promote environmentally sensitive sludge recycling to land.
- To produce a transferable, semi-distributed model predicting the environmental impact of nutrient export from non-point sources at the catchment scale.
- To evaluate whether inclusion of critical source areas (CSAs) in predictive models can improve mapping of risk areas for biosolids-amended land.
- To derive spatially-sensitive nutrient export coefficients to validate modelling of surface and subsurface flowpaths of nutrient loss from biosolids-amended land.
- To advance understanding of the form and fate of nutrients derived from biosolids applied to land.

Summary of results and conclusions

The SEAL Project is investigating whether it is possible to minimize nutrient loss by applying sludge to land outside critical source areas regardless of P Index status.

Research is underway to develop a predictive and spatially-sensitive semi-distributed model of critical thresholds for sludge application that goes beyond traditional 'end-of-pipe' or 'edge-of-field' modelling, to include delivery to receiving waters from non-point sources at the river basin scale.

The research output will be synthesized in an advice matrix (the NERM.) for end-users such as our Water Utility and Environment Agency collaborators, to determine the most appropriate form and frequency of spatially-sensitive sludge application to land to achieve sustainable sludge management without detriment to the environment and receiving water quality.

Funder(s): Defra, UKWIR, EA

Project code: PE0208

Project title: DEVELOPMENT OF OPERATIONAL GUIDELINES TO SUPPORT SAFE APPLICATION OF INDUSTRIAL BIOSOLIDS TO AGRICULTURAL LAND BASED ON A PHOSPHORUS LOSS RISK INDEX

Contractor: ADAS

Start date: 01/10/03 **End date**: 31/05/06 **Duration**: 2 years 8 months

Primary objectives

- To design of a Phosphorus Loss Risk Index (PLRI) to support safe application of biosolids to agricultural land based on current knowledge.
- To produce simple, practical guidelines on responsible biosolids, soil and land management in different PLRI areas.

Summary of results and conclusions

Project on-going.

This project will develop simple, practical guidelines on the management of land receiving biosolids in areas of different phosphorus loss risk in order to minimise possible detrimental effects on the quality of surrounding water courses, and support the beneficial recycling of a widespread resource.

Funder(s): Defra

Project code: CC0256

Project title: N_2O LOSSES FOLLOWING APPLICATION OF ORGANIC (SEWAGE SLUDGE & ANIMAL MANURE) AND INORGANIC FERTILISERS TO WINTER WHEAT.

Contractor(s): ADAS

Start date: 12.03.01 **End date**: 31.12.01 **Duration**: 9 months

Primary objectives

- To quantify and compare the N_2O emissions from plots amended with liquid sewage sludge, cattle and pig slurry and inorganic nitrogen fertiliser.
- To investigate the relationships between soil parameters (such as soil mineral N, soil water content, soil temperature and soil water soluble carbon) and N_2O emissions.

Summary of results and conclusions

1. Emissions of N_2O were enhanced by the application of both organic and inorganic fertilisers although significant differences between fertiliser treatments were not demonstrated with respect to cumulative fluxes.
2. Manure type and composition strongly influenced N_2O emissions. Sewage sludge and animal manures are applied to land in a variety of forms with quite different properties. To provide a comprehensive recommendation of the effect of organic materials, particularly sewage sludge, on N_2O emissions, it will be necessary to measure fluxes from a range of materials as well by different methods of application e.g. injection or broadcast.
3. It is highly probable that initial emissions from the organic materials are from the inorganic N fraction. Measurements are required over a longer time period (at least 1 year) in order to examine the effect of mineralisation of the organic N and the possible associated emissions.
4. The emission factors from both the organic and inorganic treatments in this study were all of the same order of magnitude, but less than the default IPCC emission factor for direct emission of N_2O from agricultural land following N fertilisation of 1.25 % of applied N. The IPCC default emission factor does not distinguish between inorganic fertilisers or organic (manures) let alone between different types of fertiliser within each category. On the basis of this study, there is insufficient evidence to support separate emission factors for sewage sludge compared to farm produced manures. It is evident, however, that the composition of the organic material can significantly effect emission and more research is required to substantiate these findings.
5. At each site and application timing the pattern of precipitation and the soil WFPS strongly influenced N_2O emissions, although only soil NO_3^--N was able to explain any of the variation in N_2O emissions.
6. The present focus on increasing the utilisation of organic wastes on agricultural land will increase N_2O emissions above those from the same quantity of inorganic N fertiliser. Further work is necessary to establish the role of the timing of waste application and possible interactions with mineral N on N_2O emissions.

Funder(s): UKWIR

Project code: 97/SL/06/1

Project title: THE CONTENT AND FERTILIZER VALUE OF SULPHUR AND MAGNESIUM IN SEWAGE SLUDGE

Contractor: ADAS, WRc

Start date: **End date:** 1997 **Duration:**

Abstract

Reviews the published data on the content and plant availability of sulphur and magnesium in sewage sludge. Surveys sludge samples from 61 centres in the UK on their sulphur and magnesium content, discusses the results and compares these sludges with animal manures. Recommends where future research effort should be concentrated.

Funder(s): UKWIR

Project code: 99/SL/08/1

Project title: BENEFICIAL EFFECTS OF BIOSOLIDS ON SOIL QUALITY AND FERTILITY - LITERATURE REVIEW

Contractor: ADAS

Start date: **End date:** 1999 **Duration:**

Abstract

Application of biosolids, usually at a rate of 250 kg N ha -1 , will typically apply 5- 8 tds ha -1 , equivalent to 2- 4 t OM ha -1 . Regular application of biosolids at this rate will lead to slow but progressive increases in soil OM content. Biosolids OM has been shown to influence a number of soil physical, chemical and biological properties, which in turn have a positive impact on soil quality and fertility. There is a requirement that the soil conditioning and fertiliser replacement value of a range of biosolids including 'new' products is evaluated under UK conditions and at appropriate agronomic rates. This would provide scientifically based information on the agronomic value of biosolids from which advisory and promotional information could be developed.

Funder(s): UKWIR

Project code: 01/SL/08/2

Project title: BENEFICIAL EFFECTS OF BIOSOLIDS ON SOIL QUALITY AND FERTILITY

Contractor: ADAS

Start date: 1998 **End date:** 2000 **Duration:**

Primary objectives

To quantify and demonstrate the beneficial aspects of biosolids use in agriculture to better inform regulators and farmer customers of its value as an organic fertiliser.

Summary of results and conclusions

Field studies were initiated at 7 sites in Britain where different types of sludge were applied for 4 years at rates above the minimum level reported in the scientific literature (c. 10 t/ha dry solids or 5 t/ha organic matter) for detectable effects on soil physical properties. The field studies showed a trend towards higher water infiltration rates at 4 of the sites on all the sludge treatments, which would decrease the potential for surface runoff and soil susceptibility to water erosion and associated sediment losses. On the lightest textured soil, there was an indication that topsoil available water capacity (AWC) had been increased by all the sludge types, with the AWC measurements increasing in order with the OM addition rates. There were also indications at several of the sites that the sludge additions had increased soil porosity and strength.

The value of sewage sludge as a source of major plant nutrients was confirmed by soil total N increases at most sites, increasing long-term crop available N supply through the mineralisation of soil organic N reserves. There were also increases in soil extractable P, total and extractable S and extractable Mg concentrations at some sites. Sewage sludge was also shown to contain useful quantities of a number of minor nutrients and trace elements (e.g. copper boron, cobalt, selenium and iodine). Liquid digested sludge applications increased grass P, Ca, Mg and Na concentrations, demonstrating that repeated sludge additions can produce grass with increased nutritional quality compared with an inorganic fertiliser control.

Funder(s): EA

Project code:

Project title: FIELD SENSOR FOR SOIL BIOLOGICAL QUALITY

Contractor: IGER

Start date: 1/8/02 **End date:** 31/3/05 **Duration:** 2.5 years

Primary objectives

To develop a field sensor for soil biological quality that will provide a rapid estimate of soil's capacity to accept sewage sludge and other waste spreading.

Summary of results and conclusions

The respiratory quotient (RQ:- ratio CO_2 produced/O_2 consumed) at a given level of soil porosity was used to define the quality of a soil by its position on a 'response surface'. As soils become increasingly anaerobic and quality deteriorates, the RQ increases and reduced gases are emitted (NOx, NH_3, H_2S and CH_4). The approach used a purpose-built apparatus in which gaseous emissions were pumped from an enclosure placed on the ground to a measurement head containing calibrated sensors and was evaluated in a one year project assessing the effects of sewage sludge cake applications to grassland. Sewage sludge cake applications decreased soil porosity and increased soil water content - effects that were still apparent after 30 days. There was also an immediate reduction in CO_2 emissions, which was most likely due to the high lime content of the cake, with longer-term CO_2 emissions (30 days) reduced by c. 30% compared with the no-sludge control. The work showed that application of high rates of sewage sludge cake (7-30 t/ha) applied to grassland had a detrimental impact on soil quality that could be quantified on the conceptual RQ/porosity response surface. As the study was limited to one type of sludge over a short time period, the effects on long-term soil quality and resilience could not be quantified.

Funder(s): EA

Project code:

Project title: COLLABORATIVE PROJECT TO UPDATE A TOOL TO DETERMINE BPEO FOR SLUDGE MANAGEMENT

Contractor: WRc

Start date: 15/1/03 **End date:** 25/3/03 **Duration:** 2 months

Primary objectives

To increase functionality (essentially increase the list of processes) of the original MASTAR software tool in line with recent political and technical developments.

Summary of results and conclusions

[Not available]

Funder(s): UKWIR

Project code: 01/SL/12/1

Project title: COMPARATIVE ENVIRONMENTAL ASPECTS OF AVAILABLE BIOSOLIDS ROUTES

Contractor:

Start date: **End date:** 2001 **Duration:**

Abstract

This study provides an independent comparison of the environmental consequences resulting from the selection of the more readily available biosolids processes and uses. Biosolids does not always enjoy a positive public image but the situation can be improved by demonstrating that biosolids use or disposal is safe and is based on a sound understanding of environmental implications.

Funder(s): EPSRC, EA, Water Companies

Project code: GR/N00012/01

Project title: PREDICTING AGRICULTURAL BENEFIT OF NOVEL BIOSOLIDS PRODUCTS

Contractor: Imperial College

Start date: 30/9/00 **End date:** 30/6/04 **Duration:** 3.75 years

Abstract

New, advanced treatment technologies are being quickly introduced by the UK Water Industry to alloy concerns about the potential risk of transmitting disease from recycling urban wastewater biosolids on farmland, which is the single most important outlet for biosolids management in the UK. The new treatment technologies radically alter the physical, chemical and microbiological properties of biosolids. However, nothing substantive is known about the use of these materials in crop production, which is fundamental to the basis of recycling on farmland. Additional wastewater treatment to remove phosphorous to avoid impacts of discharged effluents on surface water will also change the phosphate status of biosolids and, again, the significance of this for agricultural application is uncertain. For the first time, this project provides a fundamental, comparative, integrated and multidisciplinary study of the effects of advanced and nutrient removal treatment processes on agronomic value and the potential environmental impacts associated with recycling advanced biosolids products on farmland. Microbiological aspects are also considered to assess the potential risk to health and of disease transmission from land application of advanced biosolids products. Advanced treatment may extend the opportunities for recycling biosolids in the horticulture sector and these will also be investigated.

Funder(s): EPSRC, EA, UKWIR, Water Companies

Project code:

Project title: ENTERIC PATHOGEN SURVIVAL AND NUTRIENT TRANSFORMATIONS IN SEWAGE-SLUDGE AMENDED SOIL

Contractor: Imperial College

Start date: 2005 **End date:** 2007 **Duration:**

Objectives

To increase understanding of the fundamental ecological processes involved in the decay of enteric microorganisms in sludge-amended agricultural soil. Through extensive field trials, the research will focus on quantifying the intrinsic ecological dynamics that exist in the soil environment that are directly or indirectly responsible for the suppression of enteric microorganisms added to soil in sludge. The field experiments are also supporting investigations to determine the microbiological controls on nitrogen release from different types of conventional and enhanced-treated biosolids to provide a sound scientific basis to support the agronomic use of these products, thus maximising efficient use of nutrient resources in the biosolids.

Summary of results and conclusions

Microbiological analyses of untreated plots indicated that E. coli was present in unamended control soil. This background population meant that enhanced biosolids, which are treated to eliminate pathogens, had little microbiological impact when added to soil. Conventional biosolids, treated by mesophilic anaerobic digestion, contained high E. coli populations and, when added to soil, E. coli populations initially increased. During the field trial, populations of E. coli in these amendments showed evidence of decay. While they did not reach the relatively low levels seen in the control soils after 108 days, the difference in numbers between the control and the amended plots were very small and were detected due to the sensitivity of the enumeration methods employed. Certain amended plots, along with the control plots, were sampled again after 152 days. There was no statistically significant difference between the control and amended plots at one site, but due to the lower background seen in control plots at the other site, there were small, albeit significant, increase in E. coli numbers for the sludge-amended soil compared to the control. The sizes of the E. coli populations in soils following amendment, however, were extremely small when considered as a proportion of the total bacterial population in soil.

Soil microbial biomass concentrations were also recorded over the course of the field trial, and were related to organic matter (OM) content of the soils, increasing with the amount of OM in soil. The soil properties had a profound influence on microbial response to the applied biosolids. No effect of the amendments was apparent in the high OM soil, while the effect in low OM soil depended on the biomass content of the added material and substrate availability. The largest increase was observed in the plots amended with conventionally-treated sludges.

Nitrogen mineralisation investigations were also carried out. These also showed an apparent influence of soil ecological dynamics on the extent of N release from the sludges. Thus, the rate of N mineralization was lower in soil with low OM status, compared to the soil with high OM. This could be due to increased retention of N by the microbial biomass in low nutrient conditions.