NATIONAL SOILS DATABASE

END OF PROJECT REPORT

RMIS 5192

Authors

Deirdre Fay[1], David McGrath[1], Chaosheng Zhang[2], Cora Carrigg[3], Vincent O'Flaherty[3], Gaelene Kramers[1], Owen T. Carton[1], Eamonn Grennan[4]

[1] Johnstown Castle Research Centre, Wexford
[2] Department of Geography, National University of Ireland, Galway
[3] Department of Microbiology and Environmental Change Institute, National University of Ireland, Galway
[4]Institute of Technology, Sligo

Johnstown Castle Research Centre Wexford

July 2007

ISBN No. 1 84170 490 3.

AGRICULTURE AND FOOD DEVELOPMENT AUTHORITY

Teagasc Headquarters, Oak Park, Carlow

TABLE OF CONTENTS

INTRODUCTION

The objectives of the *National Soils Database* project were fourfold. The first was to generate a national database of soil geochemistry to complete the work that commenced with a survey of the South East of Ireland carried out in 1995 and 1996 by Teagasc (McGrath and McCormack, 1999). Secondly, to produce point and interpolated spatial distribution maps of major, minor and trace elements and to interpret these with respect to underlying parent material, glacial geology, land use and possible anthropogenic effects. A third objective was to investigate the microbial community structure in a range of soil types to determine the relationship between soil microbiology and chemistry. The final objective was to establish a National Soils Archive.

This project has produced a national baseline database of soil geochemistry including data point maps and spatial distribution maps of major nutrients, major elements, essential trace elements, trace elements of special interest and minor elements. In addition, this study has generated a National Soil Archive, comprising both dried soil samples and a nucleic acids (DNA) archive as well as sampling and location information for each sampling point. The terms of reference for this physical archive are presently being drawn up by the EPA, Teagasc and NUIG. This National Soil Archive represents a considerable research resource.

The *National Soils Database* has relevance with respect to environmental, agronomic and health related issues. Further benefits of the National Soil Database will arise from disseminating the findings to a wider audience including policy makers and stakeholders. As such, it will contribute to improved decision making and policy development in relation to the sustainable management of Irish soils and also for other environmental media including water and air.

MATERIAL AND METHODS

Site Description and Sampling strategy

Between 2003 and 2005, 1015 soil samples were collected in all areas of the country except the south eastern region, which had already been sampled in 1995-1996. Soil samples were collected from predetermined defined positions on the national grid (two samples per 100 km²). The grid of sampling locations (including the South East sampling locations) is shown in Figure 1.

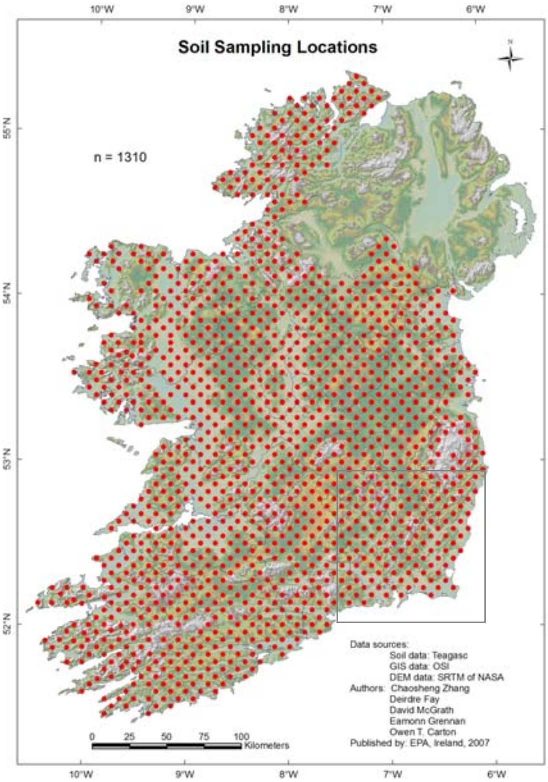

Figure 1: Map showing the grid of all the *National Soil Database* sampling locations. The extent of the original South East Study is shown in the grey frame.

At the 1015 sampling locations, soil cores were taken, using a Dutch auger, to a depth of 10 cm at 5 m intervals on a grid measuring 20 m x 20 m. Soil cores were combined to form a composite sample. These samples were added to the 295 archived soil samples taken during 1995-1996 in the south-east of the country using a similar sampling strategy. The results of this earlier sampling campaign are summarised in McGrath and McCormack (1999).

Sample Analyses

All 1310 samples were sub-sampled and these were analysed for (Al), arsenic (As), barium (Ba), calcium (Ca), cadmium (Cd), cerium (Ce), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), gallium (Ga), germanium (Ge), mercury (Hg), potassium (K), lanthanum (La), lithium (Li), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), niobium (Nb), nickel (Ni), phosphorus (P), lead (Pb), rubidium (Rb), sulphur (S), antimony (Sb), scandium (Sc), selenium (Se), tin (Sn), strontium (Sr), tantalum (Ta), thorium (Th), titanium (Ti), thallium (Tl), uranium (U), vanadium (V), tungsten (W), yttrium (Y), and zinc (Zn). In addition, soil samples were analysed for soil acidity (pH), available nutrients (P, K and Mg) and soil organic carbon (SOC).

For the microbial analysis, sub-samples were taken from the composite soil samples in the field and transferred in situ to a vial containing a stabilisation buffer that preserved the samples for microbiological analyses. This was done for all the subsamples collected during the 2003-2005 sampling campaign. A nucleic acids (DNA) archive was subsequently generated from these preserved samples by purification of soil microbial DNA and storage of the materials at -80˚C in labelled microtitre plates.

A full description of the chemical and microbial analyses can be found in the main report (Fay et al. 2007).

Data Analyses

Statistical analyses including summary statistics, probability analysis, outlier detection, data transformation, multivariate analyses of relationships identified from correlation analysis, cluster analysis, and comparisons between sample groups were applied in this study. A table including the summary statistics for all of the soil samples taken is included in Table 1 Geostatistical analyses and GIS mapping were carried out based on the results of the statistical analyses.

An output of the project was a pair of maps for each element showing concentration ranges for the element at each sampling location as point data and a spatial distribution map of concentration levels generated using the best available statistical and mapping techniques. The term level has been used in this report when referring to the spatial distribution maps as this is interpolated data generated from the actual concentrations measured. It is important to note the need for caution when using and interpreting the spatial distribution maps because of spatial variation and modelling uncertainty.

An example for each kind of map is shown for cadmium (Cd) in figures 2 and 3. The elevated levels of Cd in the centre of the country are attributed to underlying pure and impure limestone geology in these areas and not to anthropogenic effects.

A full description of the statistical methods and map generation can be found in the main report (Fay et al. 2007).

Table 1: Summary statistics and number of samples below detection (n<DL) for the 45 measured chemical properties (prop) of the 1310 soil samples in mg/kg except Avail_P, Avail_K, Avail_Mg in mg/l; SOC, Al, Ca, Fe, K, Mg, Na, P, S in %; pH in pH unit)

prop	N<DL	min	5%	25%	median	75%	95%	max
pH	0	3.2	3.7	4.6	5.3	6.1	7.0	7.7
SOC	0	1.40	2.86	4.92	7.00	14.26	48.01	55.80
Avail_P	0	0.56	2.32	4.32	7.05	12.47	30.52	316.41
Avail_K	0	4.66	45.52	82.51	124.01	181.95	312.77	949.23
Avail_Mg	0	13.49	71.11	127.51	186.13	276.28	485.92	1001.97
Al	0	0.06	0.20	2.21	3.48	4.89	6.65	9.74
As	1	<0.2	1.43	4.41	7.25	10.66	21.90	122.70
Ba	0	6.6	21.3	141.7	230.2	305.6	454.5	1296.9
Ca	0	0.026	0.102	0.225	0.358	0.613	2.591	26.628
Cd	1	<0.02	0.111	0.212	0.326	0.640	1.652	15.148
Ce	0	0.6	1.9	22.3	34.8	46.6	62.3	136.4
Co	0	0.2	0.5	3.0	6.2	9.7	15.1	58.7
Cr	44	<2	2.6	25.2	42.6	58.6	86.8	221.7
Cu	0	1.1	3.5	9.5	16.2	24.7	45.9	272.4
Fe	0	0.05	0.20	1.14	1.87	2.59	3.80	19.43
Ga	10	<0.1	0.60	5.66	8.46	12.47	17.76	25.16
Ge	72	<0.1	<0.1	0.86	1.26	1.55	2.00	2.58
Hg	11	<0.02	0.022	0.058	0.086	0.134	0.237	3.450
K	0	0.02	0.08	0.59	0.98	1.33	1.85	2.64
La	12	<0.5	1.1	12.7	20.0	25.4	33.1	75.2
Li	137	<2	<2	10.7	19.7	29.1	54.2	165.7
Mg	0	0.038	0.107	0.196	0.298	0.429	0.824	2.096
Mn	0	7	25	190	462	844	1903	21077
Mo	0	0.07	0.32	0.61	0.91	1.37	3.29	21.14
Na	0	0.015	0.053	0.205	0.338	0.545	1.091	2.254
Nb	0	0.06	0.34	4.42	6.83	8.95	12.01	38.88
Ni	0	0.8	1.9	9.2	17.5	28.6	50.0	176.0
P	0	0.007	0.036	0.075	0.105	0.136	0.202	0.493
Pb	0	1.1	11.7	18.2	24.8	33.5	61.9	2634.7
Rb	0	0.6	2.2	29.8	53.5	75.7	117.5	222.0
S	0	0.011	0.035	0.055	0.073	0.127	0.319	0.701
Sb	30	<0.05	0.10	0.31	0.53	0.85	1.54	5.29
Sc	1	<0.1	0.36	3.34	5.85	8.37	12.33	17.11

Table 1 cont.

prop	N<DL	min	5%	25%	median	75%	95%	max
Se	0	0.08	0.34	0.51	0.74	1.14	2.67	17.44
Sn	10	<0.2	0.54	1.12	1.68	2.34	4.72	17.84
Sr	0	9.2	20.7	32.5	49.7	70.1	115.0	1252.5
Ta	129	<0.05	<0.05	0.27	0.45	0.61	0.85	2.71
Th	6	<0.1	0.25	2.91	4.65	6.28	8.50	11.15
Ti	0	39	125	1355	2133	2851	3773	8704
Tl	72	<0.02	<0.02	0.292	0.430	0.568	0.818	2.664
U	20	<0.1	0.20	1.48	1.96	2.48	4.74	64.19
V	14	<2	3.9	30.8	52.2	74.2	104.8	240.3
W	132	<0.1	<0.1	0.36	0.59	0.85	1.31	7.72
Y	0	0.22	0.73	6.94	10.33	14.46	24.04	111.78
Zn	0	3.6	15.9	35.6	62.6	90.8	144.7	1384.4

Both the physical soil samples and the nucleic acids archive have been used to create a National Soil Archive. The Archive also includes a paper and electronic catalogue of standard operating procedures for the chemical and microbiological analyses undertaken. The terms of reference to access the archive are currently being developed by the EPA, Teagasc and NUI, Galway. Access to the National Soil Database will be facilitated via the National Environmental Research Centre of Excellence website of the EPA (http://coe.epa.ie/safer/).

A full report has been published (Fay et al, 2007) with an initial interpretation of the data and is available from the EPA website. The highlights of this interpretation have been summarised in the rest of this End of Project Report.

In this report when referring to the spatial distribution maps as these maps represent interpolated data generated from the actual concentrations measured and not actual local concentrations.

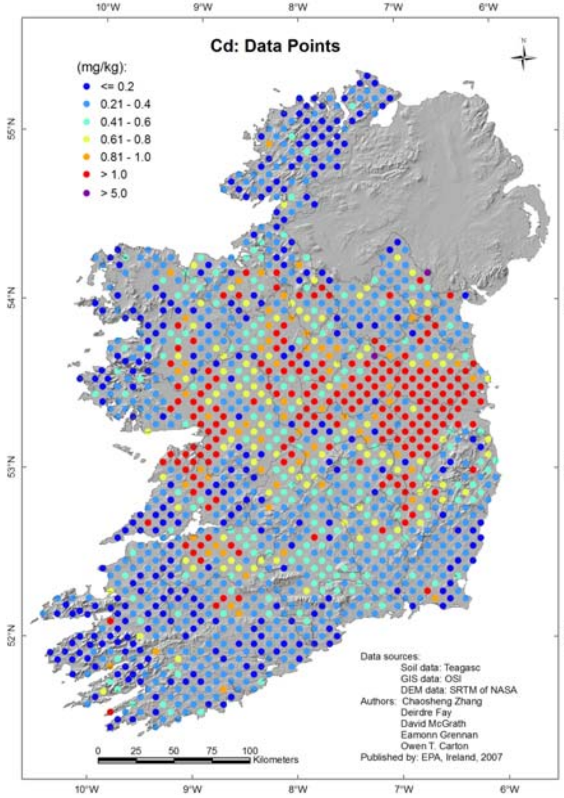

Figure 2: Cd concentration ranges measured for the data points in mg/kg soil.

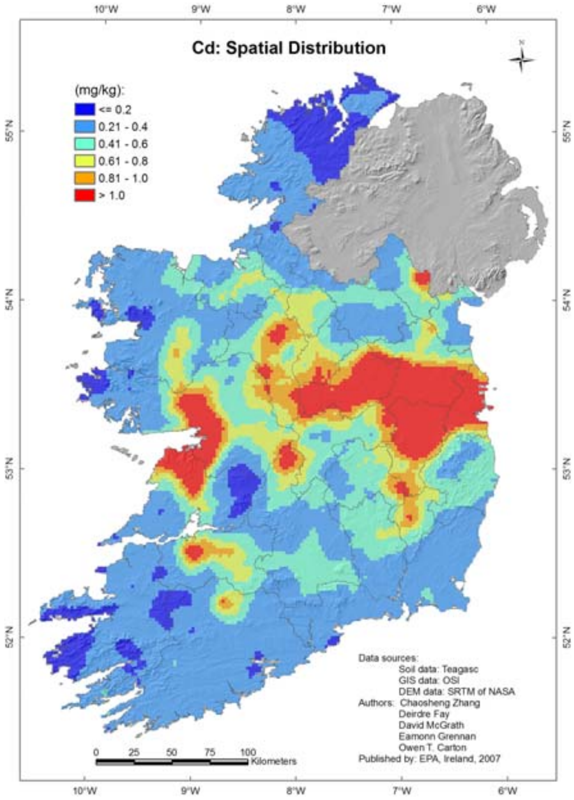

Figure 3: Spatial distribution of Cd levels in mg/kg soil.

RESULTS AND DISCUSSION

The Coherence of Soil Geochemistry with Soil type and Underlying geology

Soils are derived from parent material. This can be solid rock which has weathered, superficial deposits such as glacial drifts or alluvium or organic matter accumulated in situ. Parent material is composed of any one or a combination of these, and is strongly related to geology. The soil sampling strategy used in the National Soils Database study has allowed for an informed interpretation of the relationships between the geographical distribution of the measured geochemical data, soil types and the underlying geology.

An attempt was made to summarize the extensive geochemical dataset using expert opinion to divide the country into five major geographical regions based on the spatial distribution maps and the simplified soil and rock type maps. The general area covered in these regions is projected on the soil and rock type maps in Figures 4 and 5 and can be described as: the Central North East (A); the South East (B); Cork, North Kerry and Clare (C); Western Seaboard (D) and the Midlands (E).

The soils of the central north eastern area of the Republic of Ireland (A) consist mainly of Gleys, which have been derived from Lower Palaeozoic greywackes and shales and which have a significant volcanic mineral content. High levels of total P, total K, total Mg, Fe, Na, Al, Ti, Cu, Co, Cr and Ni were present in this region.

The soils of the south eastern region (B) consist mainly of Acid Brown Earths with subsidiary podzolics and marine derived glacial muds, underlain by a volcano-sedimentary sequence. The latter has been metamorphosed to varying degrees by the intrusion of the Leinster Granite. High levels in all or parts of this region were noted for total P, total K, Fe, Na, Al, Ti, Co and Cr. High levels of total Mg in parts of this region were attributed to either the marine-derived glacial muds or to the dolomitised limestones in counties Kilkenny and Kildare. Elevated levels of Na in this region are coincident with the Leinster granite.

The Cork, North Kerry and Clare (C) region has a few different characteristic properties. The relatively narrow geographical area of southern Cork is underlain by sandstones, siltstones and black shales. The geochemical imprint continues northwards across the Old Red Sandstones to join with the younger siltstones and grits of northern Kerry and Clare. Elevated total K in southern Cork was attributed to the underlying shales and siltstones. Elevated levels of Fe in the central and western Cork area are associated with Carboniferous shales. In western Cork and Clare, elevated levels of Al are associated with the underlying sandstone and shales. Elevated levels of total P and Cd in northern Clare are associated with phosphate rich rocks. In Ireland, seleniferous soils are typically low lying and poorly drained. These soils have been influenced to a large degree by percolating waters from Se-rich rocks where black shales are the predominant facies, and are found in northern Kerry, western Limerick and southern Clare.

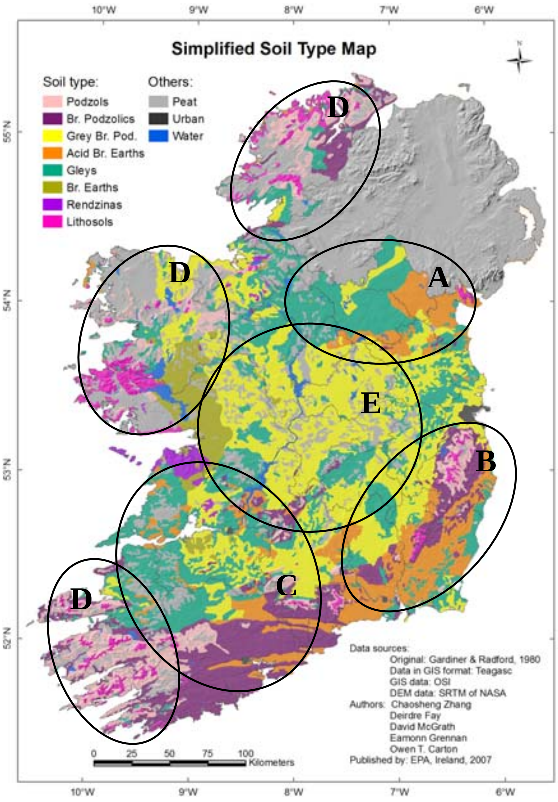

Figure 4: Simplified Soil Type map showing the five regions selected to summarise the geochemical data.

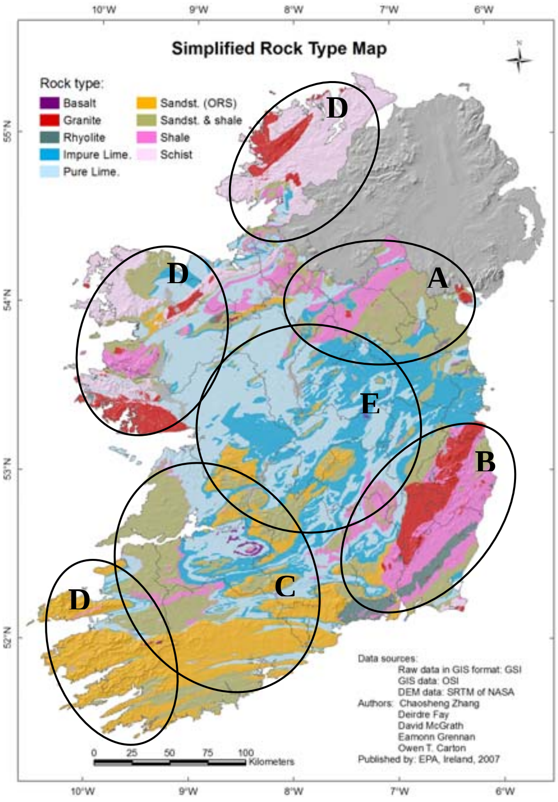

Figure 5: Simplified Rock Type map showing the five regions selected to summarise the geochemical data.

Anthropogenic and Climatic influences on Soil Geochemistry in Ireland.

The link between soil geochemistry, soil type and underlying geology was highlighted in the previous section. Soil geochemistry, in turn, has a strong influence on land use. Conversely, human activities such as mining, industry, agricultural land use with its associated farm management practice and management of sewage sludge by land spreading, can alter the chemical composition of soils.

The impact of land use and farm management practice on soil geochemical properties was particularly evident in terms of available P and available K, as well as pH. Available K concentrations closely paralleled the high available P concentrations and were coincidental with areas of intensive animal and crop production. Strong correlations were found between the soil available P and K concentrations identified in this study and those published by Teagasc based on their national database which contains in excess of 1 million results. Similarly, a good correlation was found between soil acidity (pH) in this study and published Teagasc maps for lime requirement.

Essential trace elements such as Co, Mo and Se were also considered in terms of agricultural land use and farm management practice. Low levels of soil Co, which could result in deficiencies for livestock, were apparent in the traditional sheep grazing areas of Donegal, Mayo, Galway and Kerry. The low Co levels in these soils are a result of inherently low Co in the parent material in these regions and the natural leaching of Co out of these soils. Low levels of Se were coincident with intensively managed agricultural land in the south and east of the country (e.g. Carlow, Wexford, Cork, Tipperary and Waterford); with tillage in Louth; and with coastal areas in Wexford that encompasses marine derived glacial soils.

Trace elements such as Cu, Zn, Pb and Hg, which can be toxic to livestock and plants, were considered in terms of possible anthropogenic effects. In most cases where high levels of these elements were observed, the background levels of these elements were inherently high due to the local geology. Mining and industrial activity will, however, have released more of the element into the immediate area, often elevating the concentrations further. Elevated levels of Cu were observed over broad areas of east Wicklow, along the Waterford coastline and particularly in south west Cork. These were attributed to both high natural background concentrations and the associated historic mining activities. Areas with high naturally-occurring Zn concentrations in the soil are or were associated with current and past history of Zn mines and deposits. Spot high concentration levels of Pb were coincident with the point sources of Silvermines in Tipperary and areas bordering Keady in Northern Ireland. High levels of Pb in Dublin and Wicklow are attributed to a combination of urbanisation and historical mining activity. Elevated levels of Hg in Dublin/Wicklow were attributed to an anthropogenic effect (urban and historic mining), and to the old smelter at Ballycorus, Dublin which is close to the Wicklow border. This activity has undoubtedly contaminated an area around it with a variety of heavy metals e.g. Hg and Pb.

The climatic effects on soil geochemistry observed in the dataset are due mainly to proximity to the Atlantic seaboard and to a lesser extent, being to the west of the industrial heartland of Europe. The influence of the Atlantic Ocean has manifested itself in the elevated levels of available Mg in soils on the western seaboard. This is due to the prevailing westerly winds blowing the Mg-enriched seawater overland either as rain or in the wind. There also appears to be an effect of oceanic deposition in relation to elevated levels of S and a narrow strip of elevated Na in parts of the west.

The mild temperate oceanic Irish climate which has dominated since the end of the last glaciation combined with the deforestation of the country especially since the middle of the second millennium has facilitated significant leaching of major nutrients and elements from soils leading to the development of podzols. However, in the Midlands, this leaching was significantly retarded by the high Ca content of the boulder clay, which is derived from limestone parent material and which has lead to the development of Grey Brown Podzolics.

The natural growth of Irish peats, which is intimately related to climate and biology, is well documented. High soil organic carbon concentrations (>15%) in this study reflected the peat distribution in Hammond's (1978) Peatlands Map of Ireland well, even though the samples in this study were only taken to a depth of 10 cm.

Comparative Values

A comparison was made of the Irish soil geochemical dataset with similar datasets for Northern Ireland, Scotland and England and Wales. The elements compared were Cd, Cr, Cu, Ni, Pb and Zn (Table 2).

The median Irish Cd and Pb values were similar to those for Northern Ireland and lower than those for England and Wales where there are major anthropogenic effects. The median Irish Cr value is comparable to those of Northern Ireland (Jordan et al., 2002), Scotland (Paterson et al., 2002), and England and Wales (McGrath and Loveland, 1992). The median Cu and Ni values are similar to those of England and Wales, but are lower than those reported for Northern Ireland where the background levels are enhanced by the presence of the basalts. For Zn, the median value is similar to that of Northern Ireland, and England and Wales.

Table 1: Median concentrations (mg/kg) for Cd, Cr, Cu, Ni, Pb and Zn soil for Ireland (all soils and mineral soils), Northern Ireland, England and Wales and Scotland

Element	Irish median value for all soils	Irish median value for mineral soils	Median value for Northern Ireland	Median Value for Scotland	Median value for England and Wales
Cd	0.33	0.36	0.33	0.15	0.70
Cr	42.6	48.9	46.5	41.4	39.3
Cu	16.2	18.6	27.1	7.4	18.1
Ni	17.5	20.6	29.2	17.5	22.6
Pb	24.8	24.8	17.9	23.2	40.0
Zn	62.6	72.7	65.4	48.0	82.0

It is worth noting that the observations concur with previous studies that suggest that elevated concentrations of heavy metals are generally naturally-occurring regional highs, which are a consequence of the underlying soil parent material.

Microbiological Analyses

The two main achievements of the microbial analysis section of the National Soils Database can be summarised as follows:

1. The development of a robust method for the preservation and extraction of DNA in soil which was undertaken on 1005 soil sub-samples collected between 2003 and 2005 (i.e. excluding the South East Survey, see figure 1)

2. An investigation of the bacterial community structure using denaturing gradient gel electrophoresis (DGGE) analysis. This has resulted in the genetic fingerprinting of 102 soil samples, extracted from the database using soil type and land use as selection criteria.

The use of composite soil samples, with associated stabilisation in buffer, was found to be a suitable method for microbial analysis and for generating highly reproducible and robust DGGE-based bacterial community structure profiles. This high through-put microbiological analytical approach facilitated for the first time in Ireland an investigation of the soil microbial community structure and its relationship with other soil properties.

While it is widely accepted that significant micro-scale variations in the distribution of microbial communities in soils occur; due, for example, to local crop-induced nutrient availability effects, local pH, oxygen and nutrient gradients, etc. (Torsvik et al., 1996; McDougald et al., 1998); these do not have a significant impact on the ability to generate reproducible, albeit low-resolution, bacterial community fingerprints from a variety of soils. The analysis of archived National Soils Database samples supported this view, as the reproducibility of DGGE profiles was excellent with all soils tested. While it is clear that the approach adopted here, which relied on universal primer sets, is not suitable for investigation of micro-scale variations, such as rhizosphere effects in soils, it was interesting to note that variation in microbial community structure was not an impediment to relating such wide area data together, and that bacterial community structure profiles have the potential, with further research, and a more extensive database, to be treated in a similar manner to geochemical data

Land-use management has been shown by several studies to have an effect on both the chemical composition of the soil and the structure of the microbial community (McCaig et al., 1999; Boddington and Dodd, 2000). This study also suggested an influence of crop-type on bacterial community fingerprints from bulk soil. However, due to the limited number of samples analysed, and their geographical spread, this relationship could not be definitively established.

Based on the DGGE analysis, soil type and parent material appear to be the main factors determining the bacterial community composition. A relationship was evident between combinations of soil parent material and soil type and bacterial community structure in all of the soils analysed. These results are in line with recent research (e.g. Gelsomino et al., 1999; Girvan et al., 2003).

A feature of the microbial analysis for this dataset was the occurrence of many common bands in the DGGE profiles, representing organisms from a limited number of dominant bacterial divisions (the Proteobacteria in particular) across all soils studied. These results indicate that the total bacterial community compositions are determined primarily by the underlying chemistry and physical structure of the soil rather than by the different management practices or cropping regimes. This suggests that future analysis could focus on the functional significance of these groups and could employ more specific primer sets.

CONCLUSIONS AND RECOMMENDATIONS

The *National Soil Database* provides Ireland with a robust and structured baseline of soil geochemical properties from which to assess future environmental issues and that can be used to compare future trends in the measured parameters. The *National Soils Database* will underpin Ireland's response to this the recent adoption of the European Commission's (EC) Thematic Strategy on Soil Protection (COM(2006)231final), which forms the basis for the proposed Soil Framework Directive.

To date, two new EPA-funded projects (*SoilC: Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils* (2005-S-MS-26) and *Crébeo: A National Project on Soil Biodiversity (*2005-S-LS8-M1)) are directly linked to the *National Soils Database* and its Archives. Furthermore, the *National Soil Database* is linked to an international soils research project - 'Environmental Assessment of Soil for Monitoring' (ENVASSO - Contract No. 022713).

The *National Soils Database* can provide added value in terms of policy. For example, it can provide policy guidance in relation to elements not covered by existing Statutory Instruments for the application of sewage sludge to agricultural land. Currently, no European or international agreement exists, on the basis of toxicological evaluation or even expert opinion, in relation to acceptable additions of unregulated elements that may be present in organic wastes. However, it is suggested that tentative limits may be proposed on the basis of the existing ranges reported for Irish soils in the database.

The *National Soils Database* and Archive has provided an important contribution to the development of national soils geochemical and biological information. However, this contribution to existing soils information highlights some important information gaps. No soil physical measurements were conducted as part of this project. It would be of considerable scientific value if the soil physical data (bulk density and particle size analyses) was measured at a range of soil depths for a representative number of the sampling sites used in this study. The soil samples collected should be incorporated into both soil archives as appropriate. As well as being analysed for the same suite of chemicals, these samples should also be analysed for a range of "available" and/or biologically active elements (e.g. Cu, Se, Zn, Mo, Mn and Co).

Consideration should be given to analysing the samples collected for a range of environmentally important organic chemicals. The potential impact of these contaminants (including those of agricultural and sewage sludge origin) and their long term effects on soil quality indicators is worthy of a new soils research initiative.

The availability of suitable methods for soil sampling and processing suggest that routine analysis of the microbial community structure of soils should be included in the new research. The effect of the soil type and parent material on soil's microbial community should be evaluated systematically taking into account other soil forming factors like climate, land use, and topography.

The geostatistical analyses will provide a basis for future soil geochemical risk assessment and risk management. It is recommended therefore, that the geochemical database generated be subject to interrogation with the objective of a) modelling of soil geochemical properties and their relationships with other parameters (e.g. road network and DEM); b) hotspot identification and further site investigation to determine the relevance to environmental, agronomic and health issues; and c) uncertainty analyses of the data for better quantification of the quality of the spatial maps. In addition, further interrogation of the database will aid the integration with the database for Northern Ireland and will further aid the interpretation of spatial patterns which are truncated at the border and were derived using different formats.

Further research to investigate relationships between the individual chemical parameters and the microbial data would help to understand the driving forces that regulate the bacterial community composition in soil.

It is recommended that a TELLUS-type project such as that in Northern Ireland be undertaken in the Republic. The TELLUS Programme is using state-of-the-art airborne geophysical surveying techniques, which are complemented with ground geochemical surveys. On completion, the TELLUS Programme and the Soil Geochemical Atlas of Northern Ireland will provide an integrated baseline survey of Northern Ireland. This data will have relevance for agro-economics, environmental status (e.g. ‘extreme’ concentrations), and aggregate resource management.

The *National Soil Database* and Archive has and will contribute to national and international soil research initiatives.

ACKNOWLEDGEMENTS

The authors acknowledge the invaluable contribution of the hard-working and dedicated project steering committee for their time, critical comment and encouragement. The members included: Prof. P. Loveland, Dr. E.P. Farrell, Dr. C.D. Campbell, and J. Brogan (Chair). The project team gratefully acknowledge the comments received from Teagasc research staff including Dr N. Culleton, Dr. B. Coulter, and Dr R. Schulte. Former research staff at Teagasc Johnstown Castle are also acknowledged for their expert opinion and discussion, particularly Mr S. Diamond and Dr. G. Fleming. Finally, the patience and support of the EPA Officers, H. Walsh, A. Wemaere and B. Donlon are fully appreciated and acknowledged by the project team.

REFERENCES

Boddington, C. L., and Dodd. J. C. (2000). The effect of agricultural practices on the development of indigenous arbuscular mycorrhizal fungi. I. Field studies in an Indonesian Ultisol. Plant Soil 218, 137-144.

EU Thematic Strategy on Soil protection. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. COM(2006)231final, Brussels.

Fay, D., McGrath, D., Zhang, C., Carrigg, C., O'Flaherty, V., Carton, O.T., Grennan, E. (2007). EPA report: Towards a National Soil Database (2001-CD/S2 M2).

Gardiner, M.J., and Radford, T. (1980). Soil Associations of Ireland and Their Land Use Potential – Explanatory Bulletin to Soil Map of Ireland 1980. The Agricultural Institute, Dublin. 142pp.

Gelsomino, A.A., Keijzer-Wolters, C., Cacco, G. and van Elsas J.D. (1999). Assessment of bacterial community structure in soil by polymerase chain reaction and denaturating gradient gel electrophoresis. J Microbiol Meth 38, 1–15.

Girvan, M.S., Bullimore, J., Pretty, J.N., Osborn, A.M. and Ball, A.S. (2003). Soil type is the primary determinant of the composition of the total and active bacterial communities in arable soils. J. Environ Microbiol 69, 1800–1809.

Hammond, R.F. (1978). The Peatland Map of Ireland. An Foras Taluntais, Dublin.

Jordan, C., Higgins, A. and Hamill, A. and Cruickshank, J.G. (2002). The Soil Geochemical Atlas of Northern Ireland. Department of Agriculture and Rural Development, Belfast.

McCaig, A.E., Glover, L.A. and Prosser, J.I. (1999). Molecular analysis of bacterial community structure and diversity in unimproved and improved upland grass pastures. J Environ Micro 65, 1721-1730.

McDougald, D., Rice, S. A., Weichart, D., and Kjelleberg, S. 1998. Nonculturability: adaption or debilitation. FEMS Microbiol. Ecol. 25, 1-9.

McGrath, D. and McCormack, R.J. (1999). The significance of heavy metal and organic micropollutants in soils. Teagasc End of Project Report, Dublin.

McGrath, S.P. and Loveland, P.J. (1992). The Soil Geochemical Atlas of England and Wales. Blackie Academic and Professional, Glasgow.

Paterson, E., Towers, W., Bacon, J.R. and Jones, M. (2002). Background levels of contaminants in Scottish soils. Scottish Environment Protection Agency.

Torsvik, V., Sørheim, R., and Goksøyr, J. (1996). Total bacterial diversity in soil and sediment communities—a review. J. Ind. Microbiol. 17, 170-178.