Chapter Six

Discussion

6.1 *National Soil Database* Achievements

This chapter focuses on the research highlights, key outcomes and main implications of the project. The publication of the *National Soil Database* in 2007 is timely, against the background of the adoption in September 2006, of the "Thematic Strategy on Soil Protection" by the European Commission (EC). This Strategy requires Member States to acquire a more comprehensive knowledge of their soils and soil quality and lays the groundwork for a Soil Framework Directive. This report and the National Soils Archive will provide Ireland with a sound, well structured, baseline of soil geochemical properties relevant to environmental, agronomic and public health related pressures.

6.1.1 Highlights of the National Soil Database

The main highlights arising from the *National Soil Database* project include:

- The generation of a national soil geochemical database.
- An interpretation of the database in report form.
- The establishment of a National Soil Archive which consists of the physical samples as well as a sampling and analysis manual, sampling location data and field sheets. It is comprised of two parts:
    1. A physical soils archive
    2. A soils nucleic acids archive
- The development and validation of field sampling protocols for soils for soil microbiological analyses and a robust nucleic acids extraction method.
- An initial investigation of the bacterial community structure in a variety of Irish soils.

The *National Soil Database* has produced a national database of soil geochemistry including point and spatial distribution maps for major nutrients, major elements, essential trace elements, trace elements of special interest and minor elements. 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 rather than concentration 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.

In addition, a National Soil Archive, comprised of a physical soil and a soil's nucleic acids archive, was generated which is also a significant project output. This archive represents a considerable research resource for future Irish soils research and will be available to the wider scientific community and interested parties. The terms of reference which will facilitate access to the archive are currently being developed by the EPA, Teagasc and NUI, Galway.

6.1.2 Key Outcomes of the National Soil Database

A number of key outcomes relating to the *National Soil Database* are worth mentioning.

- The geographical coherence of the geochemical results and their reflection of the underlying geology and parent material.
- Evidence of land use, anthropogenic and climatic effects.
- A strong relationship between parent material and microbial data.

The geographical coherence of the results is noteworthy given that the soil samples were taken to a depth of 10 cm and at a sampling density of only two samples per 100 km^2. This coherence, e.g. between the elements Co, Cr, Fe, As, Mn, Cu and Mg is further discussed in section 6.2 of this chapter. It is predominantly influenced by the underlying parent material and glacial geology.

The effects of land use, anthropogenic activity and climate effects were evident for a number of elements in various areas of the country. The distribution of available P and K was largely related to agricultural practises, with relatively high levels coincident with areas where intensive agriculture is practised. Occasional spot highs of some heavy metals were attributed to mining activity, for example high Pb levels around Silvermines in Tipperary and Keady mine in Monaghan. Oceanic deposition of Se and available Mg was evident along the western Seaboard. These and other features are discussed in sections 6.3. and 6.4 of this chapter.

This study applied large-scale microbiological analysis of soils for the first time in Ireland and in doing so also investigated microbial community structure in a range of soil types in order to determine the relationship between soil microbiology, soil type and parent material, soil geochemistry and land use. The results of the microbiological analyses, discussed in section 6.5 of this chapter, were consistent with the geochemical analyses and demonstrated that bacterial community populations were predominantly determined by soil type and parent material.

6.1.3 Implications of the National Soil Database

The *National Soil Database* generated baseline soil geochemical maps (point and spatial distribution) and has begun an interpretation of these with respect to geochemical and pedological aspects. The database has implications for environmental, agronomic and public health related issues including:

- Providing a robust referenced baseline to assist in Ireland responding to European environmental and, in particular, soil policy.
- Assisting in the identification of risk areas and suitable baseline values in terms of the recently adopted EC “Thematic Strategy on Soil Protection”.
- Establishing a database and archived soil resources for current and future soil research.
- Highlighting that heavy metal concentrations of some soils exceed those thresholds established by the Sewage Sludge Directive.
- Providing a robust database which identifies areas with both elevated and deficient concentrations of elements which may have implications for environment, agronomy and public 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. The potential implications of the *National Soil Database* for policy are discussed in section 6.6 of this chapter.

6.2 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 observed coherence in the distribution of concentration levels of many elements can be, to a large extent, explained by the soil types and their underlying geology.

6.2.1 Geology of Ireland

For a country of its size the geology of Ireland is extremely varied, ranging from rocks over 1500 million years old to peat deposits which are still growing. The reasons are basically three-fold. Ireland was divided by the Iapetus Suture 450 million years ago; it is at the land edge of the present Eurasian tectonic plate, which incorporates the eastern side of the Atlantic Ocean and during the past two million years it has endured at least three glacial episodes. The first two of these have combined to produce a very diverse geology, compared to many European countries and/or regions. Irish geology encompasses metamorphic rocks which vary from quartzites to schists and gneisses; igneous rocks which vary from large granite intrusions to small volcanic centres; and a series of sedimentary rocks including greywackes, shales and siltstones, coarse sandstones and in particular a wide range of limestones varying from very pure to very argillaceous. The sedimentary rocks, of Carboniferous age underlie over half of the country (Fig. 4.1).

6.2.2 Glacial Geology

The most recent countrywide map of glacial geomorphology (Synge, 1979) is over 25 years old. Even though the glacial episodes have been much studied, a question is often raised “from where is the bulk of the material in the soil derived?” The general operating consensus has been that the bulk of the material in the soil has travelled at most 5 km, and much of it less than 2 km. The extent of transportation of glacial material has been considered within the context of this report. On the one hand, data from Northern Ireland (TELLUS Programme, www.tellus.detini.gov.uk) strongly suggests that the transport distance of most glacial material is approximately 500 m. On the other hand, there is widely acknowledged evidence of features of glacial erratics which occur in the landscape. For example, granite originating from the island of Ailsa Craig demonstrates a transport distance of more than 200 km. In addition, field derived data (EPA Soil and Subsoil Mapping Project, Teagasc, 1998-2006) has shown that, in a small number of areas, a mantle of till (up to 1 m deep at a distance of 15 km from its source) has been derived from bedrock situated up-ice overlying a deeper till of local derivation. However, these situations are exceptional, and in such cases, Smyth (GSNI, pers. comm.) feels that sufficient time has elapsed since the last glaciation for the geochemical fingerprint of the underlying glacial material to be imprinted on the overlying layers. Thus, it would be surprising if the glacial transport of material markedly influenced the distribution maps presented in this report as these were based on a 10 km by 10 km sampling grid.

6.2.3 Geographical Coherence

In the early stages of both the planning and execution of this project, there was some concern about the low sampling density (two samples per 100 km^2). However, as pointed out in Chapter 4, the spatial effects displayed by geostatistics were numerous and included both elevated and low levels of elements. The south eastern geochemical study (McGrath and McCormack, 1999) which used the same sampling density but without geostatistical analysis appeared to show that the sampling density used could give a coherent set of results. The sampling strategy has, through robust spatial analysis, shown the baseline geochemistry of the soils of Ireland in a clear and unequivocal manner and has allowed better understanding of the relationships between these properties, soil type and underlying geology. For example, the coherence between the elements As, Co, Cr, Cu Fe, Mg and Mn can predominantly be explained by the underlying parent material. The high levels coincide to a large extent with the sandstones and shales in the country, whilst the low levels are associated with underlying limestone.

An attempt was made to summarise this extensive geochemical dataset using expert opinion to divide the country into five major geographical regions based on observations of the measured elements from the spatial distribution maps and the simplified soil and rock type maps. The general area covered in these regions is projected on the rock type map in Figures 6.1 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). In Table 1, elements have been highlighted for each region on the basis of relatively high (h) or low (l) observed levels of the element compared to the other regions. The denotation (o) means that localized high or low levels were observed. This table is an observational summary of the extensive information in the maps and can be used as a guide to identify links between geomorphologic regions and the relative concentrations of the measured chemical elements in the maps. Some of the geographical coherences identified in Table 6.1 are discussed below.

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

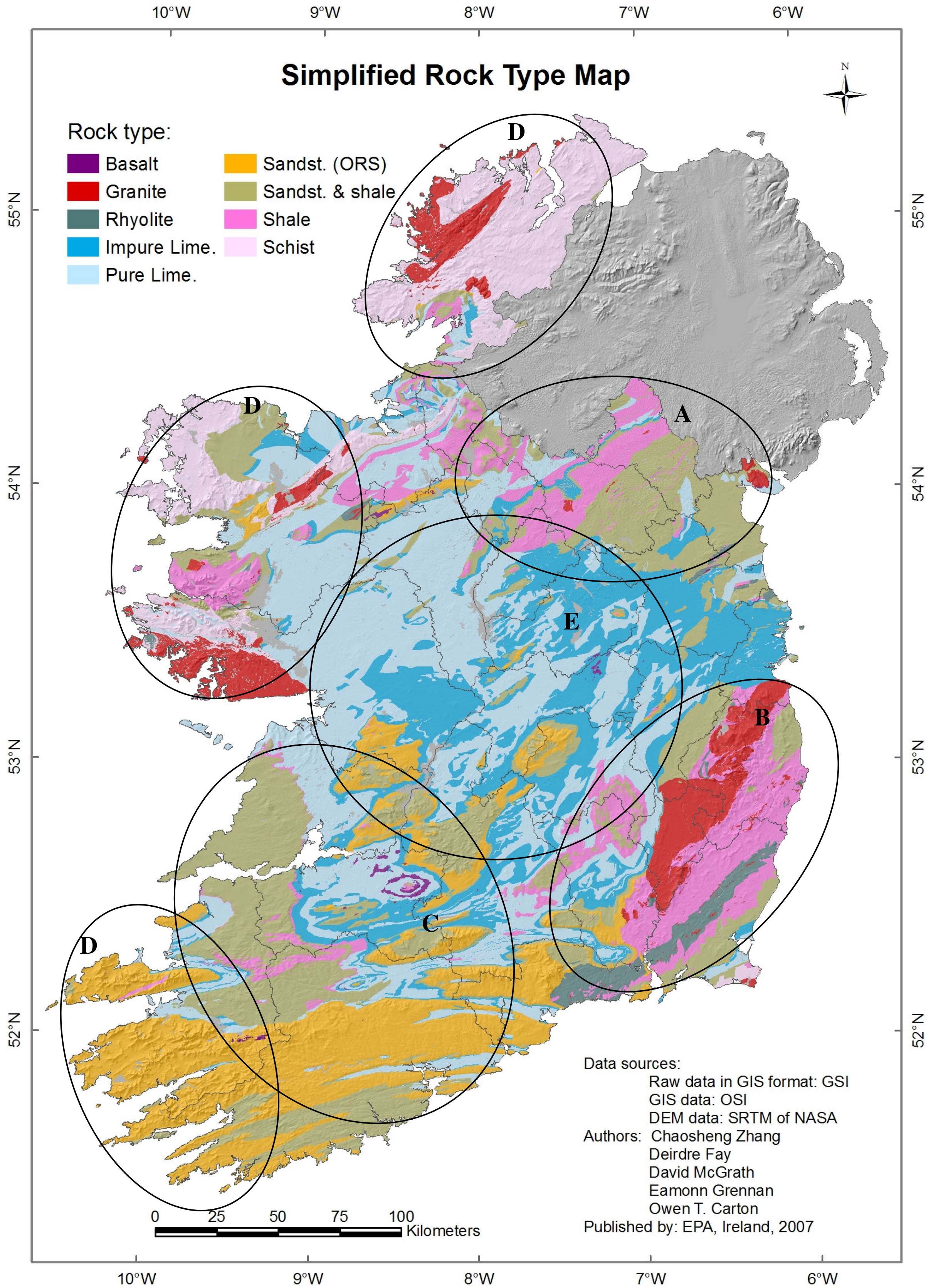

Figure 6.1 Simplified Rock Type map showing the five regions selected to summarise the geochemical data.

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. It was noted that Al and Fe show similar distribution patterns. 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.

The over-riding effect of the "blanket peat" is visible all along the Western Seaboard (D). A soil organic carbon content of ≥15% was defined in this study as the delineation between mineral and peat soils.

While elevated levels of S in the west, north west and midlands were attributed to an organic matter effect, low levels of Na, As, Cr, Cu and Co were observed in organic rich soils around the country. It was noted in this study that Cu and Co were negatively correlated with organic C.

The largest area of all, the Midlands (E), is dominated by Grey Brown Podzolic soils, with smaller areas of "raised peat". The former have been derived from either pure limestones or impure limestones, each of which has left its own geochemical fingerprint. Low levels of Fe are found in Roscommon and parts of Mayo, Galway and Clare which are underlain by pure limestone. Low levels of Na and Cr are associated with limestone areas generally. Elevated levels of Zn mirror the occurrence of underlying impure limestones in Dublin, Meath, Westmeath and Kildare (or karstified limestones as in the Allenwood area of Kildare). Seleniferous soils are found in areas with underlying impure limestone geology, such as Dublin, Meath, Westmeath, west Offaly, east Galway and north Tipperary. Elevated levels of Cd in Dublin, Kildare, Meath, Westmeath, north Tipperary and Roscommon are attributed to underlying pure and impure limestone geology in these areas rather than anthropogenic effects.

Table 6.1: Observed relatively high/low levels of elements for the geographical regions from the spatial distribution maps. Observed localized high/low levels are marked with an (o).

Geographical Region	Elements associated with the Region
Central North East (A)	**h**: Al, Co, Cr, Cu, Fe, Ga, K, La, Mg, Na, Ni, P, Sc, Sr,V, Zn **l**: S, Se
South East (B)	**h**: Al, As, Ba, Co, Cr, Fe, Ga, Ge, K, La, Li, Mg, Mn, Na, Nb, Pb, Rb, Sb, Sc, Sn, Ta, Ti, V, W **l**: Ca, Cd, S, Se
Cork/North Kerry/Clare (C)	**h**: Al, As, Cd(o), Ce(o), Cu(o), Fe, Ga, Ge, K, La, Nb, Ni(o), P(o), Sc, Ta, Th, Ti(o), Se(o) **l**: Ca, Li, Mg
Western Seaboard (D)	**h**: S, Se, Sr(o), SOC **l**: pH, most measured elements
Midlands (E)	**h**: Ca, Cd(o), Mo(o), S(o), Se(o), SOC(o), Y(o), Zn(o) **l**: Al, Ce, Cr, Ga, Ge, La, Li, Mg(o), Na(o), Nb, Ta, Th, Ti, V, W

6.3 The effect of Parent Material and Human Activities for some specific elements

The chemical composition of the parent material from which a soil is formed will, in most cases, have a strong influence on that of the soil itself. Human activities which can influence the chemical composition of a soil include agricultural, horticultural and silvicultural land use, farm management practices, landspreading, the management of sewage sludge, mining, industrial activities and transport. The influence of parent material and human activities were considered either separately or in combination across a range of specific elements and the results are discussed below.

6.3.1 Major Elements

The impact of micro-geographical factors, related to management practices at farm scale, are particularly evident for the concentrations of available P and available K, as well as pH observed in the soils database.

Available P and available K

Many of the regions identified with high concentrations of available P can be explained by the land use in the area. High available soil P concentrations in Louth, east Dublin, south east Wexford and north west Kerry are due to tillage farming and vegetable growing on light textured soils. High concentrations in north Carlow and south Kildare may be due to intensive tillage on limestone derived soils. High concentrations in east and central Cork are due to a combination of intensive livestock and tillage farming on very good soils, while the high concentration of available P in the Cavan and Monaghan region is probably associated with the intensive poultry and pig enterprises in these counties (Coulter *et al.,* 1999). In east Clare and east Galway, the explanation for elevated extractable P concentrations may be the presence of shallow calcareous soils as P is more readily extracted from these. The high concentrations of available K closely parallel the high concentrations of available P as illustrated by geostatistical analysis and are mostly associated with areas of intensive agriculture.

Soil acidity

It was noted from the spatial distribution maps (Fig. 4.35) that the majority of higher (basic) pH soils occur in the south east of the country, where intensive tillage is the predominant agricultural activity. This is a result of the lime additions associated with tillage land use. There is a very good relationship between the pH map (Fig. 4.35) and the Teagasc Lime Requirement Map (Coulter *et al.,* 1999).

6.3.2 Essential Trace Elements

Cobalt, Mo and Se are discussed below in terms of both deficiency (Co and Mo) and toxicity (Mo and Se) perspectives.

Cobalt

Historically in Ireland, Co deficient soils were seen to exert a negative influence on livestock health, particularly sheep (Walsh *et al.,* 1955). A Co concentration of < 5 mg/kg in soils is indicative of deficiency (Walsh, 1952). Lower levels of Co were apparent in Donegal, Mayo, Galway and Kerry which were traditionally sheep grazing areas. In considering Co deficiency, it should be noted on mineral soils that it is most likely to be related to either the low Co content of the parent material (granite) or that it has developed as a consequence of leaching.

Molybdenum

High concentrations of Mo in Irish soils are often associated with the presence of Namurian shale in the parent materials. These high concentrations are not confined to any single great soil group but occur in Grey Brown Podzolics, Acid Brown Earths and Gleys (Finch and Rogers, 1978). Molybdenum in grassland is important from both deficiency and toxicity perspectives. Deficiency affects clover establishment by influencing N fixation, whereas excess Mo in pastures can give rise to animal health problems. Excess Mo in pasture induces a Cu deficiency in grazing animals (Parle *et al.,* 1998). In general, the occurrence of elevated Mo in Ireland is more likely to create a challenge compared with Mo deficiencies.

Selenium

Soils with Se concentrations greater than 5 mg/kg are considered to be potentially toxic. In this study, low concentrations of Se in soils were more evident. Comparatively low Se soils were coincident with agricultural land in the south and east of the country (e.g. Carlow, Wexford, Cork, Tipperary and Waterford); with tillage land in Louth; and coastal sandy soils in Wexford, which encompasses marine derived glacial soils. Low Se soils (<0.5 mg/kg) also occur in parts of east Galway and east Clare on light-textured soils derived from parent material with low Se concentrations.

Seleniferous soils occur sporadically throughout the country and can have Se concentrations of several hundred mg/kg (Walsh *et al.,* 1951). This is the result of the localised character of Se rich outcrops. Typically, the black shales of Namurian (mid-Carboniferous) age, the parent material for these soils, occur in localised outcrops with high Se concentrations (Fleming, 1982). In the present study, 'Extreme' or high concentrations of Se were noted at some locations. Indeed there are more extreme Se values than for any other element but their occurrence is very sporadic. Anthropogenic sources of Se include coal burning and mining activities. This may explain the slightly elevated levels in Wicklow (Fleming pers. comm.). Furthermore, a strong effect of deposition/retention was observed in the organic-rich soils along the west coast. Steinnes (2005) has previously reported evidence of biogenic emissions of volatile organoselenium compounds from the ocean, which has lead to an excess of Se in the terrestrial environment along the Norwegian coastline.

6.3.3 Trace Elements of Special Interest

Four trace elements mentioned in Chapter 4 as being of special interest include Cu, Zn, Pb and Hg. They can be toxic to livestock, plant and soil organisms where uptake is excessive.

Copper

Examples of elevated concentration of Cu associated with historical mining activities are evident over broad areas in east Wicklow, along the Waterford coastline and particularly in south west Cork. Reilly (1986), for example, reported frequent Cu bed showings in the south Cork area, where at least 42 mineralised veins are known. There is also a close association between As and Cu on the south coast of Cork and in the south east and this related to both the incidence of historic mining activities and natural high background concentrations. The maximum threshold concentration for Cu in the receiving soil under the EU Sewage Sludge Directive is 50 mg/kg. However, in this study less than 4% of soil samples exceeded this threshold.

The Cu content of Irish sewage sludge can be very variable with values reported by O'Riordan *et al.*, (1986) ranging from 86 to 5500 mg/kg dry matter. There are regional anthropogenic effects associated with elevated Cu concentrations. The application of pig slurry has added Cu to Irish soils. Pig slurry contained Cu at concentrations of 600 to 800 mg/kg dry matter (McGrath *et al.,* 1982), though more recently Cu concentrations in pig diets have been reduced. The application of Cu sulphate (bluestone) for potato blight was widespread in the past. The elevated levels of Cu in Dublin/Meath are attributed to anthropogenic effects, particularly mining.

Zinc

Naturally-occurring regional highs are associated with current and past history of Zn mines and natural Zn deposits. For example, during initial prospecting carried out at the Lisheen (Tipperary) Zn-Pb-Ag deposit, now one of the most important Zn producing mines in Europe, low level anomalies (150 mg/kg Zn) were enhanced using computerised geochemical maps (Hitzman et al, 1992). The discovery of a Zn-Pb deposit in Kildare was based on the identification *circa* 1969 of a "a low order zinc anomaly (635 mg/kg Zn)" at a depth of 0.5 m, which was enhanced with more detailed sampling to a maximum value of 2400 mg/kg Zn (Emo, 1986). The spot high at the border in Monaghan is related to Keady Mine in Northern Ireland. It was observed that concentrations of Zn around Silvermines in Tipperary are not particularly elevated, although this may have been expected from the results of previous work done in this area (Mcgrath, 2004). This may be a direct result of the sampling intensity. While the maximum threshold concentration for Zn in soil under the EU Sewage Sludge Directive is 150 mg/kg, only 4% of samples analysed in this study exceeded that threshold.

Lead

The maximum threshold concentration for Pb in soil under the EU Sewage Sludge Directive is 50 mg/kg. Approximately, 9% of soil samples analysed exceeded this threshold in the current study. Spot highs of Pb were coincident with Silvermines in Tipperary and in the north east they were related to Keady mine. Elevated concentrations of Pb in Dublin and Wicklow are attributed to a combination of urbanisation (largely related to the past use of leaded petrol) and the historic working of lead.

Mercury

Mercury has been shown to be associated with some of the Zn-Pb deposits present throughout the midlands, and the sulphide deposits in Wicklow. Elevated concentrations in Dublin/Wicklow are also attributed to an anthropogenic effect (urban and historic mining), including the old smelter at Ballycorus, Dublin close to the Wicklow border, which has undoubtedly contaminated an area around it with a variety of heavy metals including Hg and Pb. The maximum threshold concentration for Hg in soil under the EU Sewage Sludge Directive is 1 mg/kg. There were three values in the dataset that were greater than this threshold.

6.3.4 Comparative values

A brief comparison was made of the new Irish soil geochemical database with similar datasets for Northern Ireland (Jordan *et al.,* 2002), Scotland (Paterson *et al.,* 2002), and England and Wales (McGrath and Loveland, 1992). The elements compared were Cd, Cr, Cu, Ni, Pb and Zn as shown in table 6.2.

The median Irish Cd value, similar to that for Northern Ireland, is lower than that for England and Wales where there are major anthropogenic effects. The median Irish Cr value is comparable to those of Northern Ireland, Scotland, and England and Wales. 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 concentrations are enhanced by the presence of the basalts. The median Pb value is similar to that reported for Northern Ireland and Scotland, but lower than the value reported for England and Wales where anthropogenic effects including Pb smelting for nearly 2000 years have resulted in elevated soil Pb concentrations. For Zn, the median value is similar to that of Northern Ireland, and England and Wales.

It is worth reiterating the findings of this study, which concur with previous studies that suggest that elevated concentrations of heavy metals are generally naturally-occurring regional highs, which can be attributed to the underlying soil parent material.

Table 6.2: Table with median values for Cd, Cr, Cu, Ni, Pb and Zn in mg/kg of soil for the Ireland (all soils and mineral soils), .Northern Ireland, England and Wales and Scotland databases.

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

6.4 Observed Climatic Effects

The climatic effects observed in Ireland are due mainly to our proximity to the Atlantic seaboard and to a lesser extent our location being to the west of the industrial heartland of Europe. The influence of the Atlantic Ocean has manifested itself in the elevated concentrations of available Mg in soils. 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 concentrations of S and a narrow strip of elevated Na in the west and northwest. By contrast, elevated levels of available Mg in Wexford are due to the presence of the marine derived till and low-lying coastal areas in this region.

The mild temperate oceanic climate experienced by Ireland since the end of the last glaciation, and the deforestation of the country especially since the middle of the second millennium, has given rise to extensive podzolisation of Irish soils, leading to significant leaching of major nutrients and elements. However, this leaching is significantly retarded in the characteristic Grey Brown Podzolic soils which have formed on limestone parent material. The basic character of the boulder clay in the midlands, which is derived from limestone parent material, means that leaching in these soils is slower. In this study, elevated levels of Ca and low levels of Al were associated with Grey Brown Podzolics.

The natural growth of our peats, which is intimately related to climate and biology, has been well documented. As previously noted, there was a good correlation between Hammond's (1978) Peatlands Map of Ireland and elevated soil organic carbon in this study.

6.5 Microbiological Analyses

Based on the microbiological data presented in this report, the following observations can be made.

The use of composite soil samples, with associated stabilisation in buffer (Appendix A), was found to be a suitable method for soil sampling in this study and for generating highly reproducible and robust microbial DGGE-based bacterial community structure profiles. 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.

The considerable variations encountered between the DGGE profiles generated from a particular soil sample, using the four different DNA extraction methods tested here, are in agreement with the findings of previous research (Kozdrój and Van Elsas, 2000; de Lipthay *et al*., 2004), and highlight the fact that, for simultaneous analysis of multiple soil types and samples, a single, standard method of nucleic acid extraction and processing must be employed to generate comparable data.

The choice of DNA extraction procedure should, in general, be influenced by soil type, but also by the requirements of subsequent analyses i.e. PCR, DNA hybridizations. For large-scale studies of a variety of soils, however, a single method must be employed. Based on the criteria of DNA yield, richness (or apparent biodiversity) and the reproducibility of results between multiple experiments involving a wide variety of soil types, Methods 2 and 3 (Chapter 5) are both highly suitable for large-scale soil research studies and are recommended for future use. Method 3 may have an additional advantage of facilitating the simultaneous analysis of the active and total bacterial fractions in soils (Griffiths *et al.,* 2000), but this requires further research to determine feasibility. In this study, Method 2 was slightly advantageous compared to Method 3 with respect to lysis efficiency and reproducibility of DGGE profiles, and was selected as the method of choice.

Despite the inherent biases associated with PCR-based methods (Suzuki *et al.,* 1996, 1998), relative comparisons between microbial communities, based on such methods, have been routinely applied to the study of microbial diversity within soils. The main advantages are: (i) they overcome the problem of the low culturability of the majority of microorganisms in soil; (ii) they allow for rapid, high-throughput analysis; and (iii) they are amenable to statistical and comparative analyses. In addition, several reports investigating the effects of target DNA dilution or decreasing numbers of PCR cycles have suggested that PCR biases may not be significant when applied to 16S rRNA gene-based community fingerprinting (Felske *et al.,* 1998; Osborn *et al.,* 2000). Nevertheless, when such data are used to calculate diversity and equitability indices, these values should be considered relative to those for other samples within a given study and not as absolute values. In general, these PCR-based methods are currently the most representative and efficient methods for comparison of microbial community structure and diversity within environmental systems.

The microbial community profiles, generated by this project, were clearly related to soil parent material and soil type. Furthermore, their geographical coherence paralleled the geochemical patterns outlined in Table 6.1. This finding is in line with recent reports which also suggested that soil type (Girvan *et al.,* 2003) and parent material (Ulrich and Becker, 2006) are key determinants of bacterial community structure in soils.

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.

Despite variations in many chemical and biological soil characteristics, samples of similar soil type, from geographically distinct locations, often exhibited almost identical rRNA-derived DGGE banding profiles and formed similar clusters after analysis. It is likely, therefore, that the total bacterial community compositions are determined primarily by the underlying soil chemistry and texture rather than by the different management practices or cropping regimes at these sites. Spatial homogeneity of bacterial communities in soil, over distances of several hundred metres, was also revealed in Dutch meadows by genetic fingerprinting by Felske and

Akkermans (1998), where almost identical DGGE profiles were generated between samples, suggesting that despite heterogeneity in soil properties, the dominant members of the microbial community appeared to be ubiquitous in the particular area studied. A feature of the data presented in Chapter 5 was the presence of many common bands, representing organisms from a limited number of dominant bacterial divisions (the *Proteobacteria* in particular) across all soils studied, which suggests that future analysis could focus on the functional significance of these groups and could employ more specific primer sets. To this end, promising results were obtained in this study when the *amo*A-targeted primer set was used to investigate the diversity and community structure of a particular functional group, the ammonia-oxidising bacteria, in a range of soils. Although the sample numbers tested were limited, dominant clusters were identified, common to all samples, and the diversity of ammonia oxidisers appeared to be greater in grassland than in arable soils (Section 5.6).

6.6 Relevance to Policy

6.6.1 Thematic Strategy on Soil Protection

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 future response to the requirements of the European Commission's (EC) Thematic Strategy on Soil Protection, which forms the basis for the proposed Soil Framework Directive.

The Thematic Strategy on Soil Protection requires securing and maintaining a comprehensive knowledge of soil quality and quantifies this by identifying eight threats to soil. Of these eight, five threats (soil erosion, organic matter decline, salinisation, compaction and landslides) will require risk assessment methodologies to identify areas at risk for each threat. The *National Soil Database* and archives will provide baseline data for the risk assessments for some of these threats both in terms of potential locations for monitoring sites and the chemical and biological parameters to be considered. In addition, the proposed Soil Framework Directive may require Ireland to set risk reduction targets for the areas at risk, establish programmes of measures to achieve them and monitor their progress. There is a further proposed requirement to identify contaminated sites and establish a national remediation strategy aimed at reducing soil contamination and the potential associated risks. In the context of agricultural systems, limited national information exists on the effects of soil contamination with heavy metals or veterinary residues (such as antibiotics and hormones) on soil quality. The *National Soil Database* and Archive will provide a reference point in the identification of sites or areas contaminated with heavy metals.

6.6.2 Other European Directives and Policy

The *National Soil Database* will provide baseline soil geochemical and microbial data for current and future European environmental directives and policy. The Water Framework Directive (WFD) addresses eutrophication of waters and sets out a framework for the implementation of a comprehensive system for the management of water resources with the objective of maintaining a 'high status' of water quality where it exists, preventing any deterioration in the existing status of waters and achieving a 'good status' in all waters by 2015. It is interesting to note that a similarity exists between the "Thematic Strategy on Soil Protection" and the WFD in that both require risk assessment, programmes of measures and reduction targets with respect to the protection and long term sustainability of soil and water resources. The Nitrates Regulations, which came into force in 2006 (S.I. 378 of 2006), established a series of nutrient management measures for agriculture to address eutrophication. Land use change and CAP Reform that affect farming practices may also have an impact on soil processes and soil quality, and some of the specific requirements such as those relating to the Good Environmental and Agricultural Conditions (GAEC) of soils are directly relevant to soil protection and the threats to soil quality. The *National Soils Database* and Archive will provide an important baseline dataset which will contribute to the establishment and evaluation of the national monitoring environmental programmes that will be used to assess the effectiveness of the measures.

6.6.3 Sewage Sludge Directive

The provisions of the Sewage Sludge Directive (86/278/EEC), which is transposed into national legislation by the Waste Management (Use of Sewage Sludge in

Agriculture) Regulations 1998-2001, set threshold values for the concentration of heavy metals in soils receiving sewage sludge. The maximum Irish soil concentrations are as follows: Cd (1 mg/kg soil), Cu (50 mg/kg soil), Hg (1 mg/kg soil), Ni (30 mg/kg soil), Pb (50 mg/kg soil) and Zn (150 mg/kg soil). It is evident from this study that thresholds in some soils are exceeded for one or more of these elements. In the case of Hg, Cu, Pb and Zn elevated levels were attributed to a varying combination of natural levels and anthropogenic effects including mining, industrial, land use and urban activities. The situation with respect to Ni and Cd is more problematic. This study found that at a national level, 15% of soils exceeded the threshold value for Cd, while 23% of soils exceeded the threshold value for Ni. These elevated soil heavy metal concentrations are attributed to the composition of the soil parent material rather than to anthropogenic effects, except on a very local scale. For example, there appears to be a relationship between the Grey Brown Podzolic soils (and limestone parent material) and elevated Cd levels in Westmeath, northern Tipperary, Roscommon and eastern Galway. The high percentage of soils exceeding the threshold level for Cd (1mg/kg) in Dublin and neighbouring counties can therefore be explained for the most part, by the dominating soil type and parent material.

The data and maps pertaining to these regulated metals will provide valuable insight for Irish policy makers involved in any future European discussions and negotiations concerning proposed amendments to the soil metal threshold values already established in the Sewage Sludge Directive. In addition, they will provide Irish policy makers and managers with important data required when defining concentration limits for the spreading of organic waste.

6.6.4 Application to Soil Policy

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 (cf. Section 3.3). 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 availability of suitable methods for soil sampling and processing suggest that routine analysis of the microbial community structure of soils can be incorporated into soil protection and monitoring programmes.

6.7 Application to Future Soil Research

The *National Soil Database* and Archive has and will contribute to national and international soil research initiatives. 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 main objective of this European funded project is to harmonise existing national datasets, to form a central reference point to assess current soil status and to ensure sustainable management in the future. There is considerable potential for further linkages with the large scale EU funded Framework Programme 7 (FP7).

The national soils nucleic acids archive has a potentially highly significant role in a wider research context. The cloning of large fragments of soil DNA into expression vectors has already been successfully used to mine the soil metagenome (or gene pool) for novel anti-microbial drugs, for enzymes for industrial applications, for compounds with anti-tumour activity, for anti-fouling agents and a host of other potentially valuable compounds. These studies are based on the analysis of DNA extracted from soil and the fact that such a diverse and comprehensive soils archive is available is (to our knowledge) unique in an international context, although many other countries are now developing large-scale metagenomic projects (e.g. the NERC marine metagenomic project in the U.K). The bio-prospecting of the archive in projects will be expensive using the currently available methods, although potentially extremely rewarding. It is likely, however, that methods to access the soil metagenome will become cheaper and more rapid in the near future, which will encourage more interest in this field. Given the potential socio-economic value of the archive, both European projects and national programmes are likely to seek access to the archive for research purposes in the near future.

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 (e.g., 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).

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.

Consideration should be given to analysing the samples collected for a range of environmentally important organic chemicals where still possible on the dried samples. 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 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.

The re-sampling of the south-east region of Ireland, to complete the nucleic acids archive is recommended, as the fundamental value of the archive with respect specifically to soil science is extremely important.

As presently constituted, access to the nucleic acids archive is severely limited due to potentially irreversible loss of material arising from thawing and re-freezing on the quality of the DNA. It is recommended that an additional 10 copies of the archive be created and stored using a more accessible system to provide adequate coverage of future national research needs.

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 (www.tellus.detini.gov.uk) 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.