3. The Tellus geochemical surveys, results and applications

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Ambitions to complete geochemical mapping across the island of Ireland were developed in the 1980s and the first phases began in western Northern Ireland in the early 1990s. Subsequent phases in Northern Ireland and the Republic of Ireland were begun from 2004. The Tellus and Tellus Border geochemical sampling programmes of 2004–12 resulted in the most comprehensive maps of their kind for the northern region of Ireland. These programmes covered 30% of the island of Ireland, albeit at different sampling densities, with detailed soil and stream sampling. Soils were sampled at 10,335 sites and streams at a further 9501 sites. 1269 urban sites were sampled in Belfast and Derry–Londonderry. The survey methodologies followed the established sampling protocols of the GB Geochemical Baseline Survey of the Environment (G-BASE). Applying these systematic approaches of sampling and quality control was the foundation for developing coherent and comparable cross-border data sets. The samples were analysed by internationally accredited laboratories. In all media, typically around 55 inorganic chemical elements and ions, and physico-chemical properties were analysed and measured. The maps of these elements reveal wide variations across the area, reflecting the influence of the underlying geology, mineralisation, and anthropogenic and environmental factors. The data, which are open and freely available, have prompted an increase in mineral exploration and research into a range of environmental questions.

Introduction

Geochemical mapping contributes to several areas of economic development and environmental management:

- by defining a standard (or 'baseline') for the chemical composition of soils, stream sediments and stream waters;

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- by detecting and mapping higher than normal levels of potentially harmful elements and compounds in soils and surface waters;
- by mapping the chemical attributes that influence the sustainability of biodiversity and habitats and that influence plant, animal and human health;
- as an essential tool in prospecting for economic minerals.

The chemical composition of rocks varies widely, according to their origin and history. Over time, soils and stream sediments are produced from rocks by weathering and erosion. To a large extent soils and sediments retain the chemical composition of the original rock and therefore their chemical compositions reflect the nature and constituents of the original source rocks. However, at a particular site, soil has not necessarily formed only from the rock beneath but may have been transported from elsewhere by wind, water or ice. Some chemical constituents of the soil may also have been subsequently dissolved and leached away, while others may have been introduced from elsewhere. Interpretation of soil chemistry maps is therefore complex and requires an understanding of the behaviour and mobility of different elements and compounds under various physical and chemical conditions.

By sampling and analysing sediments from streams in an individual catchment we can map the elements that have been mobilised from their source elsewhere in the catchment and have been concentrated in the stream bed. Stream sediment chemistry maps therefore reflect the variation and concentration of mobile elements from the whole area of the catchment, in contrast to the soil chemistry maps, which are compiled from individual and well-separated samples.

The analysis of soils for their trace-element geochemistry originated as a prospecting tool in the USSR in the 1930s and by the 1950s was a well-established method, notably in the US, Canada and Scandinavia. The methods were developed for exploration in the UK and British Commonwealth from the 1950s by Professor John Webb (1920–2007) at Imperial College, whose teams undertook the first regional survey in Northern Ireland in the 1970s (Webb *et al.*, 1973). Since then, the processes of sampling, analysis and interpretation have continued to be developed for regional rural and urban mapping, notably by the British Geological Survey's G-BASE programme (Johnson *et al.*, 2005).

Maps of the metallic elements in soils and streams may show anomalies reflecting a local increase in concentration. Most metals of economic interest occur in association with other elements and this association is a valuable indicator, or pathfinder element, for the prospector. A notable example in the north of Ireland is the association of arsenic with gold.

Sampling and analysis of stream water enable us to map the distribution of soluble elements and compounds, acidity, electrical conductivity and dissolved organic carbon.

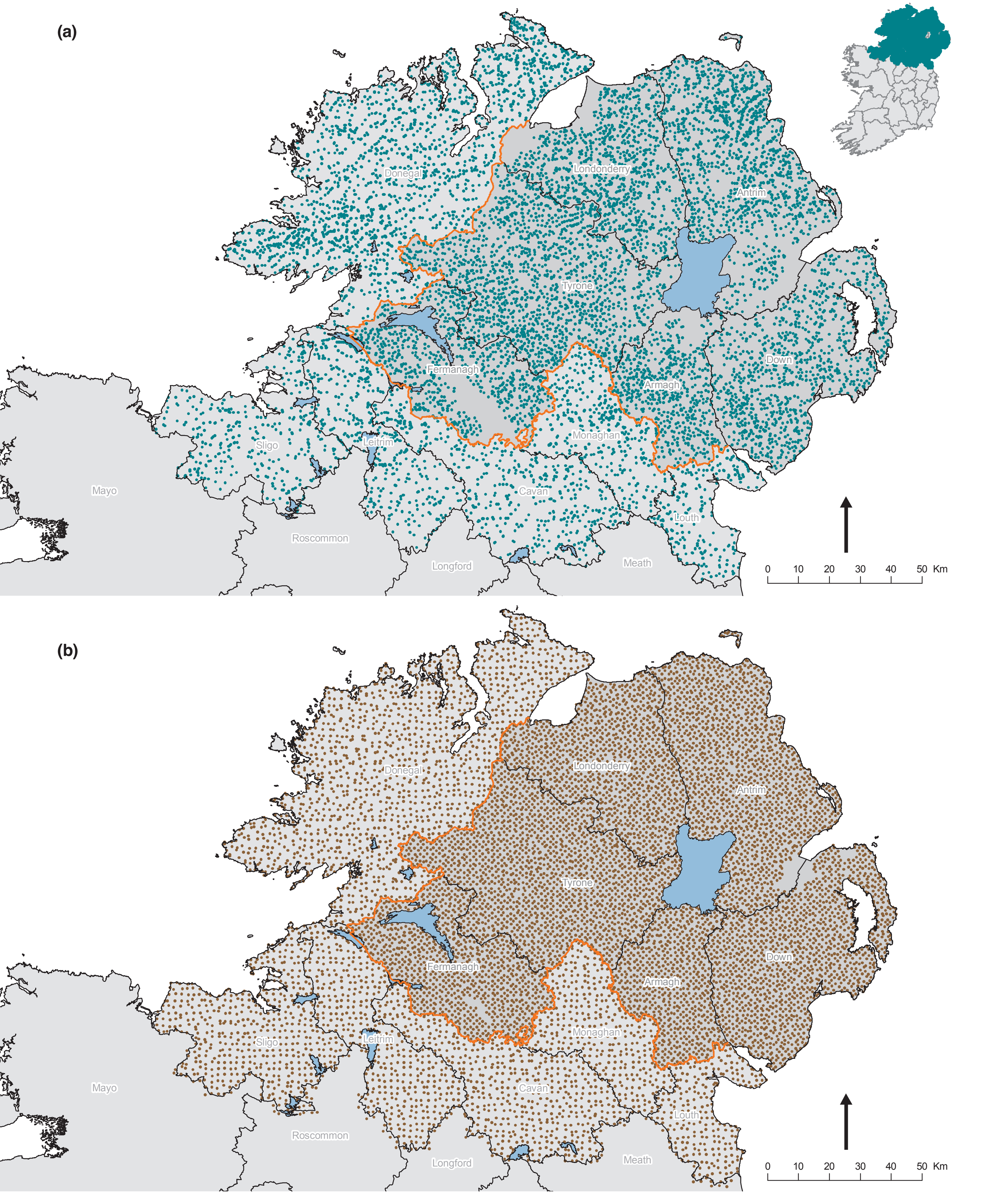
Previous regional geochemical surveys in Ireland

The first regional geochemical survey in Northern Ireland, by the Applied Geochemistry Research Group of Imperial College, London, mapped the concentrations of a suite of trace elements in stream sediments and detected anomalies associated with the mineralisation in western Northern Ireland (Webb *et al.*, 1973). The results prompted the mineral prospecting and mining development that continue today.

The next regional survey in Northern Ireland was a drainage survey undertaken in the mid-1990s by the British Geological Survey (BGS) in the western half of the region, at a density of one sample per 2.25 km^2 (Flight *et al.*, 1998). This survey was undertaken to the G-BASE standard and the resulting data have been incorporated into the Tellus Project. In 2000 the Department of Agriculture and Rural Development (DARD) published an atlas of soil geochemistry of lowland areas of Northern Ireland based on 6000 samples taken on a 1 × 1 km grid (Jordan *et al.*, 2000). This work raised interest in the importance of trace elements in agricultural management.

In the north of the Republic of Ireland regional reconnaissance stream sediment geochemistry surveys were undertaken in 1985 by the Geological Survey of Ireland (GSI) in the Inishowen peninsula, County Donegal (O'Connor *et al.*, 1988). Almost 200 sites were sampled at a density of approximately one sample per 4.5 km^2. Other areas sampled included part of the Longford–Down Terrane and an area of south-east Ireland. Between 1995 and 2002, a National Soil Database project undertaken by Teagasc and the Environmental Protection Agency was completed nationally in Ireland, in which 1365 topsoil samples were collected at a nominal sampling interval of one site per 50 km^2, to provide a geochemical baseline for soils relevant to environmental and agronomic objectives (Fay *et al.*, 2007). In 2009 the GSI in collaboration with the Norges Geologiske Undersøkelse (Geological Survey of Norway) completed a regional baseline urban geochemistry survey of the greater Dublin area, comprising 1058 topsoil samples taken at a nominal density of one per 1 km^2 for inorganic elements and at a lower, variable density for selected organic compounds (Glennon *et al.*, 2014).

Ireland as a whole has been included in three European geochemical baseline projects. The Global Geochemical Baselines Programme, coordinated in Europe by the Forum of European Geological Surveys (Salminen, 2005), has informed the development of national geochemical baselines. As part of this study stream water, stream sediment and soil samples were taken at a nominal density of 1 per 100 km^2. Secondly, the international GEMAS survey (a collaboration between Eurogeosurveys and Eurometaux) provided harmonised geochemical data of arable land and land under permanent grass cover at the continental European scale, with a sample density of one site per 2500 km^2 (Scanlon *et al.*, 2013; Reimann *et al.*, 2014a, 2014b). Most recently Ireland has participated in the LUCAS project, which collected selected physical and chemical property data on cropland topsoils (Tóth *et al.*, 2013).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Antrim
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Figure 3.1. (a) Stream sample sites; (b) soil sample sites.

Geochemical survey operations

The geochemical sampling and laboratory analysis programmes have been described in detail by Smyth (2007) and Knights and Glennon (2013) for the Tellus and Tellus Border surveys, respectively.

In the Tellus surveys of Northern Ireland, sampling of soils and streams ran over several field seasons between 2004 and 2006 and was managed by the Geological Survey of Northern Ireland (GSNI) with support from BGS. The programme employed relays of university students, more than 80 being involved over the course of the operation, operating from field bases throughout the region. The Tellus Border soil and drainage sampling campaigns were undertaken by OCAE Consultants Ltd, under the direction of GSI, and took place in a concentrated operation between August 2011 and June 2012.

The methods used for sample collection and analysis followed the protocols set out by G-BASE and the protocols comply with national and international standards for the handling of geological samples.

Table 3.1. Geochemical sampling sites in rural areas

	1994–1996 Western NI	2004–7 NI	2011–12 RoI
Soils ‘A’ and ‘S’	–	6862	3475
Sediments	2908	2966	3626
Stream waters	2846	3063	3542

Table 3.1 and Fig. 3.1 show the number and distribution of sites sampled for the Tellus and Tellus Border surveys. In addition, 1269 soil sites were sampled in the Belfast Metropolitan Area and in the City of Londonderry (Knights, 2007; Nice, 2010).

Streams were sampled at an average sampling density of one site per 2.4 km^2 in Northern Ireland and at one site per 3.4 km^2 in the Republic of Ireland. Soils were sampled at an average sampling density of one site per 2 km^2 in Northern Ireland and one site per 3.6 km^2 in the Republic of Ireland. The urban soils were sampled at four sites per km^2.

The same sampling methodologies were employed for the two surveys and the same sample types were collected, except for two instances: in the Tellus survey, rock was sampled at 114 additional sites; in the Tellus Border survey, vegetation samples (woody or twig material) were collected at stream sample sites.

Stream sediment and water sampling

Field teams chose sampling sites mostly on first- or second-order streams, upstream of any potential source of contamination. Sediment samples were obtained by sieving to collect

Figure 3.2. (left) Stream sediment sampling; (right) soil sampling.

the fraction finer than 150 µm (Fig. 3.2). At each site a heavy-mineral sample was also collected by *in situ* panning of material that had been passed through a 2 mm sieve. Samples were air-dried at the field base and shipped to the laboratory for analysis.

Water samples were collected slightly upstream of the stream sediment site to avoid contamination by sediment disturbed during sampling. Separate samples were taken for analysis of inorganic elements, total organic carbon (TOC) and pH/alkalinity/electrical conductivity.

Soils

Soil samples were collected by hand-augering in five different positions within a 20 × 20 m square and then amalgamating the collected soil into one sample (Fig. 3.2). Samples were taken from two depths: 'A' samples (or 'surface soils') from 5–20 cm and 'S' samples ('deep soils') at 35–50 cm. Observations of soil colour, depth, clast lithology and abundance were also recorded. Duplicate samples were taken regularly for quality control.

Samples were dried before shipment to the laboratory. Here the sample was sieved to separate the fraction finer than 2 mm and from this a representative 30 g subsample was taken. This subsample was then finely ground in an agate ball mill prior to analysis.

Chemical analysis

Contracts for analysis were awarded by tender to accredited laboratories; the details of these processes and the quality control procedures applied are given by Smyth (2007), Knights and Glennon (2013) and Knights (2013a). Samples were analysed by X-ray fluorescence (XRF), inductively coupled plasma (ICP) spectrometry or both; Knights (2013b) presents the details of the surveys and analyses carried out on the various sample types (Table 3.2).

Data integration of the two Northern Ireland data sets

The samples from the Tellus stream survey of 2005–6 were analysed for a greater range of elements and with lower detection limits than had been possible with the 1994–6 samples. The two sets of sediment samples were analysed by XRF using the same procedures. The disparity of detection limits of the two surveys was counteracted by presenting sediment data sets for the whole of Northern Ireland using the 1994–6 detection limits. Where required, the more recent data from the eastern half of Northern Ireland may be plotted separately to take advantage of the lower detection limits in this survey. During each phase of sampling sufficient quality control procedures, notably the use of control samples, were deployed.

For the Northern Ireland stream waters, improvements in analytical instrumentation were also significant between 1996 and 2005, but it proved possible to merge the data sets for most analytes; only arsenic (As), chromium (Cr) and nitrate (NO_3) were presented as separate data sets for the 1994–6 and 2005–6 surveys. In order to provide an assessment of temporal variability between the two surveys, a group of water samples was collected in a common north–south zone which overlapped the eastern margin of the 1994–6 stream sampling area and the western margin of the Tellus sampling area. Analysis of these samples indicated similar values for a range of analytes.

Data and image processing

The main software employed for map production was ArcGIS 9.2. The design of the map template was based on the G-BASE process and the same colour gradient and statistical techniques were used to represent the geochemical data set.

Regional data sets were imported into ArcGIS and grids of each element were produced using the 'Spatial Analyst' extension. For the Northern Ireland data (Smyth and Johnson, 2013), the parameters of gridding were those routinely used for producing interpolated images in the G-BASE programme, i.e. inverse distance weighting (IDW) with a grid cell size of 250 m, a fixed search radius of 1500 m and power value of 2. For the merged Tellus and Tellus Border geochemical maps, IDW was also employed but a larger search radius was used (3000 m for soils, 2000 m for sediments), reflecting the lower sampling density in the Tellus Border region. For all maps, colours are allocated in the images according to a percentile classification scheme.

Table 3.2. Summary of chemical analyses

	Tellus	Tellus Border
'A' soils		
pH, loss on ignition	•	•
Multi-element analysis by XRF	•	• *
Multi-element analysis by ICP (aqua regia digest)	•	•
'S' soils		
pH, total organic carbon	•	
Multi-element analysis by ICP (aqua regia digest)	•	
Multi-element analysis by ICP (four-acid digest)	•	
Platinum group elements analysis by fire assay	•	
Sulphate analysis	•	
Sediment		
Multi-element analysis by XRF	•	•
Boron analysis by ICP	•	
Platinum group elements analysis by fire assay	•	•
Waters		
pH, alkalinity, conductivity	•	•
Multi-element analysis by ICP	•	•
Anion and NPOC by ion chromatography	•	•

Fire assay	The most accurate method of measuring concentrations of precious metals in a sample, by which the metals are separated by firing the sample to a very high temperature. Used to analyse for gold and PGE.
ICP	Inductively coupled plasma spectrometry, a method of analysing elemental concentrations in a liquid. Solid samples are prepared for analysis by digesting with an acid solution. The aqua regia acid digest solution is a mixture of nitric and hydrochloric acid. The four-acid solution (as applied to the 'S' samples) dissolves elements and compounds that resist aqua regia and provides concentrations that are 'near-total'.
Ion chromatography	A method of analysing anions and cations in a liquid sample.
LOI	Loss-on-ignition is a proxy for the proportion of carbon in soil obtained by burning off combustible material in a previously dried sample.
NPOC	Non-purgeable organic carbon: analysis of a filtered water sample to determine its dissolved organic carbon (DOC) content.
PGE	Platinum group elements: ruthenium, rhodium, palladium, osmium, iridium, and platinum.
pH	A measure of the acidity/alkalinity of a sample.
Sulphate analysis	Determined on 'S' samples by dilute hydrochloric leach followed by ICP.
TOC	Total organic carbon.
XRF	X-ray fluorescence spectrometry, a method of analysing the elemental concentrations in a solid sample.

* Multi-element analysis by XRF was completed for Tellus Border soils in 2015 and data are due to be published in 2016.

Aspects of interpretation

Stream sediments

The geochemical images show the concentrations of the chemical elements (expressed as oxides for the major elements) in the <150 μm fraction of stream sediment samples.

The chemical compositions of the samples give an indication of the composition of the catchment bedrock. However, the chemical composition of the fine fraction of a stream sediment sample may differ from the typical composition of the bedrock in the source area, particularly:

- where bedrock is overlain by Quaternary deposits or by glacial or other extraneous material that has been transported into the stream;
- if chemical and physical weathering of the parent rocks has altered the composition of the source rock and thus the sediment derived from it;
- where bedrock is coarse-grained, such that some minerals with larger grain size are selectively removed by sieving during sample collection;
- where oxides of iron and manganese have been precipitated in streams causing absorption of other trace elements dissolved in the water, potentially producing very high concentrations of these elements in the fine fraction of the sediment;
- if sediment contains anthropogenic contamination, such as pollution from industry, agriculture or domestic sources.

Soils

The geochemistry of soils is related to the characteristics of bedrock geology, superficial deposits, land use, climate and topography. Soil typically contains rock and mineral fragments in various states of weathering and alteration; clay minerals produced by the weathering process; other secondary minerals; living organisms; varied organic matter and possibly contaminants.

In temperate climatic zones, in many soils lying on non-carbonate bedrock, minerals and organic material are leached downwards from the upper 'A' horizons of a soil and redeposited by precipitation in the lower 'B' horizon, a process referred to as podzolisation.

Thus, a comparison of soil and stream sediment geochemistry may reveal both similarities and differences. The more important physical differences include: (i) a lower rate of material transport within soils, allowing more time for in-profile modification by leaching and other processes; (ii) a greater influence of site geology, rather than catchment geology; (iii) usually only partial water saturation; and (iv) often extensive anthropogenic modification in both agricultural and urban areas.

Soils in intensively farmed agricultural areas are further modified by physical disturbance (e.g. ploughing) and chemical treatment (liming, fertilisers, pesticides), which may affect both the major nutrient elements, such as calcium (Ca), potassium (K) and phosphorus (P), and supplement trace elements, such as zinc (Zn).

Stream waters

Stream water geochemistry is strongly controlled by bedrock and superficial geology, which in the north of Ireland vary widely, both in chemical composition and in physical properties. Other factors that influence stream water chemistry include:

- atmospheric deposition and rainwater composition;
- terrestrial flora and fauna;
- mineral weathering;
- groundwater composition and residency time of groundwater;
- catchment hydrology and extent;
- anthropogenic influences in the terrestrial, marine and atmospheric environment;
- in-stream processes such as chemical precipitation and mobilisation.

The occurrence, behaviour and general geochemical characteristics of different elements in soil, stream sediments and stream waters have been summarised by Breward and Chenery (2013).

Applications of the data

Regional interpretations of the Northern Ireland soils data have been presented by Smyth (2013); of the stream sediment data by Flight and Lister (2013); and of the waters by Ander (2013). Knights (2013c) presented and discussed the integrated results of the Tellus and Tellus Border surveys, and a detailed description of the integrated topsoil and sediment data has been compiled by Gallagher *et al.* (2016a, 2016b). Here we summarise the main applications of these data.

Geological mapping

Much of the bedrock of the north of Ireland is overlain and obscured by glacial deposits and peat, but the geochemistry of soils and sediments has nevertheless been shown to be representative of bedrock. Breward *et al.* (2011) compared the stream sediment geochemistry for the Tellus survey with that for sediments overlying equivalent Lower Palaeozoic bedrock in southern Scotland. Despite the much thicker cover overlying the bedrock in the Down–Armagh area of Northern Ireland, the principal geochemical lineaments identified in Scotland are still apparent, with patterns of the distribution of several elements demonstrating the continuity of structure and stratigraphy between the two regions. Stream sediment and soil data for the merged Tellus/Tellus Border region emphasise the strong bedrock control of stream sediment and soil geochemistry, with major geological units (Antrim basalts, the Longford–Down inlier, Caledonian granites in counties Donegal and Down, Carboniferous sequences in the south-west) strongly delineated (Gallagher *et al.*, 2015a, 2015b). The patterns apparent on the geochemical maps have been reinforced by

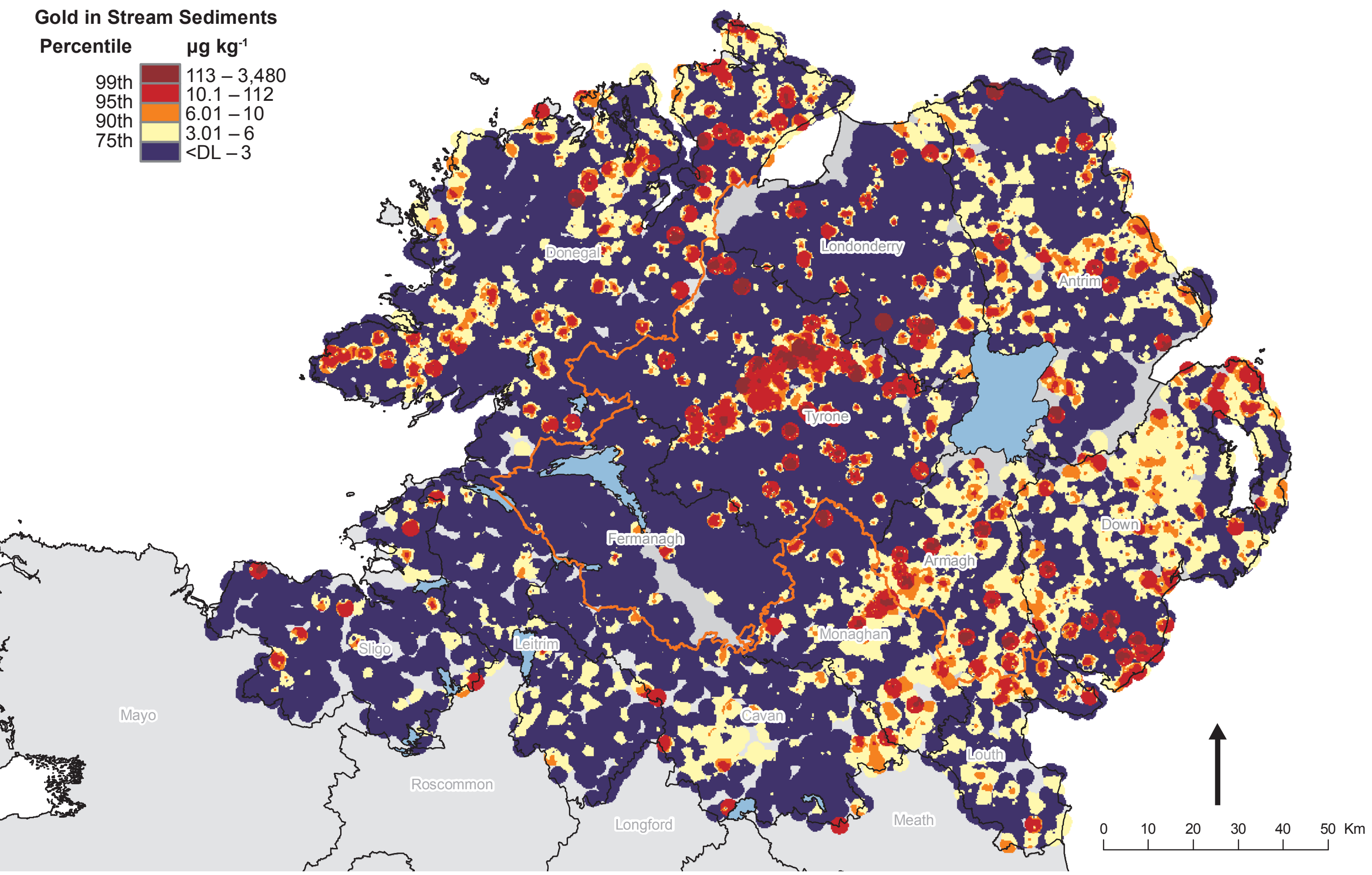

Figure 3.3. Gold in stream sediments.

Appleton *et al.* (2011), who, in a statistical analysis, calculated that 83% of the variation in uranium in 'A' soils in Northern Ireland can be ascribed to bedrock geology. Geochemical surveys are therefore a valuable support to the revision of geological mapping in covered areas, which is now taking place in both Geological Surveys.

Mineral exploration

The mineral potential of the north of Ireland is well known and has been the subject of many campaigns by government, academia and industry. Numerous mineral prospects and deposits, including former mines, occur throughout the region. Commodities that have been mined or explored for include metallic elements such as gold, lead, zinc, iron, copper, antimony, industrial minerals such as gypsum, barite, salt and perlite and fuel minerals including coal and lignite (Mineral Deposits of Ireland Map, Exploration and Mining Division 2009). A primary objective of the Tellus initiative was to stimulate further exploration by producing modern, detailed geochemical and geophysical data.

The map of gold in stream sediment (Fig. 3.3) shows numerous anomalous zones spread across the entire area covered by Tellus and Tellus Border. The most prominent of these, overlying the Dalradian rocks south of the Sperrin Mountains in County Tyrone, includes the two deposits at Curraghinalt and Cavanacaw (Arthurs and Earls, 2004). This zone has been known since Webb *et al.* (1973) first mapped the associated arsenic anomalies, but the

Figure 3.4. The Clay Lake Nugget (3.6 × 2.1 cm, 28 g) (© National Museums Northern Ireland Collection Ulster Museum).

Tellus data provide greater resolution and definition. Other potentially significant if less extensive gold anomalies in the Dalradian rocks lie to the west and north-west, extending into County Donegal. Some are now the subject of detailed exploration.

Anomalous gold concentrations were detected in sediments overlying much of the Lower Palaeozoic Longford–Down terrane of counties Down, Armagh, Monaghan and Cavan. Significant stream sediment gold anomalies occur: in north County Down, possibly reflecting an association with the mineralisation north of Newtownards at the old Whitespots–Conlig mine; around the old mining district of Castleblayney–Keady in north County Monaghan and south County Armagh, where extensive exploration in recent years has revealed significant gold prospects at Clontibret and Clay Lake (Fig. 3.4); and further south-west around Slieve Glah in County Cavan.

Small clusters of anomalies occur throughout the area. Some may reflect gold dropped by glacial movement, but sympathetic increases in the concentration of other metals such as zinc, lead, tin and arsenic indicate that the area is generally mineralised. Dempster *et al.* (Chapter 7, this volume) analysed the distribution of gold and pathfinder anomalies in soils in this area. They found that their spatial patterns are strongly or subtly influenced by glacial movement but that the distance travelled is not great. This method of analysis appears to be a valuable means of validating anomalies in areas covered by glacial material.

High levels of gold occur in the stream sediment data on the southern margin of the Eastern Mournes Centre of the Palaeogene Mourne Mountains Complex, perhaps originating from bedrock gold in the Mourne Mountains.

Lusty *et al.* (2009, 2012) used the Tellus data for Northern Ireland, together with geophysical and geological data, to analyse mineral prospectivity with the statistical process of 'fuzzy logic' in two areas, the Dalradian of County Tyrone and the Lower Palaeozoic Longford–Down terrane. These analyses used the attributes of known mineralisation to identify further zones for investigation. Coulter and Stinson (2013) used 'A' soils and stream sediment data for pathfinder elements, together with geological criteria, to prioritise targets for prospecting in the Tellus Border area.

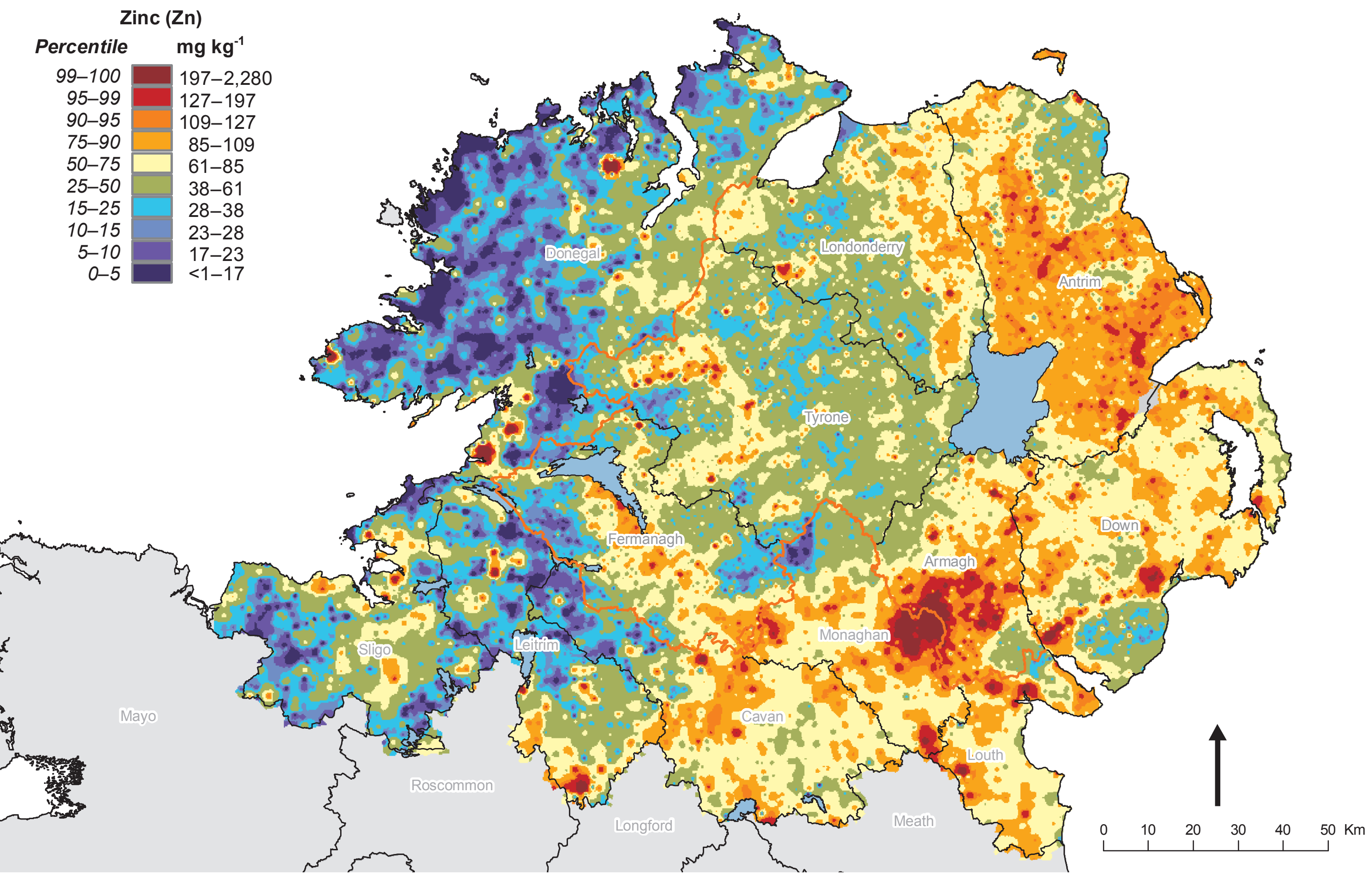

Figure 3.5. Zinc in 'A' soil.

There is a long history of exploitation of lead and zinc in this region, notably around Castleblayney–Keady in County Monaghan and County Armagh, at Conlig–Whitespots in County Down and in Carboniferous rocks at Abbeytown, County Sligo. Both soil and sediment geochemistry maps show lead and zinc anomalies in these areas, particularly in counties Down, Armagh and Monaghan (Fig. 3.5). The Tellus data have prompted a fresh appraisal of the Tyrone Igneous Complex of County Tyrone; Hollis *et al.* (Chapter 12, this volume) describe how Tellus geophysical and geochemical data have improved our understanding of its potential for hosting volcanogenic massive sulphides and demonstrate a correlation with the highly mineralised Buchans–Robert's Arm arc system of Newfoundland.

The apparent resolution of the geochemical maps can be improved by a statistical approach that incorporates the closely spaced airborne radiometric data with the more widely spaced geochemical data, as demonstrated by McKinley *et al.* (2014) for an area of County Tyrone prospective for base metals. The approach produced more detail in the geochemistry imaging, notably of the mapped distributions of zinc, copper and lead.

The mapping of geochemical anomalies in platinum group elements, notably in the Antrim Basalts, has encouraged an international mining company to prospect in this area.

The worldwide and national supply of so-called 'critical metals' is currently a matter of concern. Lusty (Chapter 8, this volume) examines the regional potential for these in the

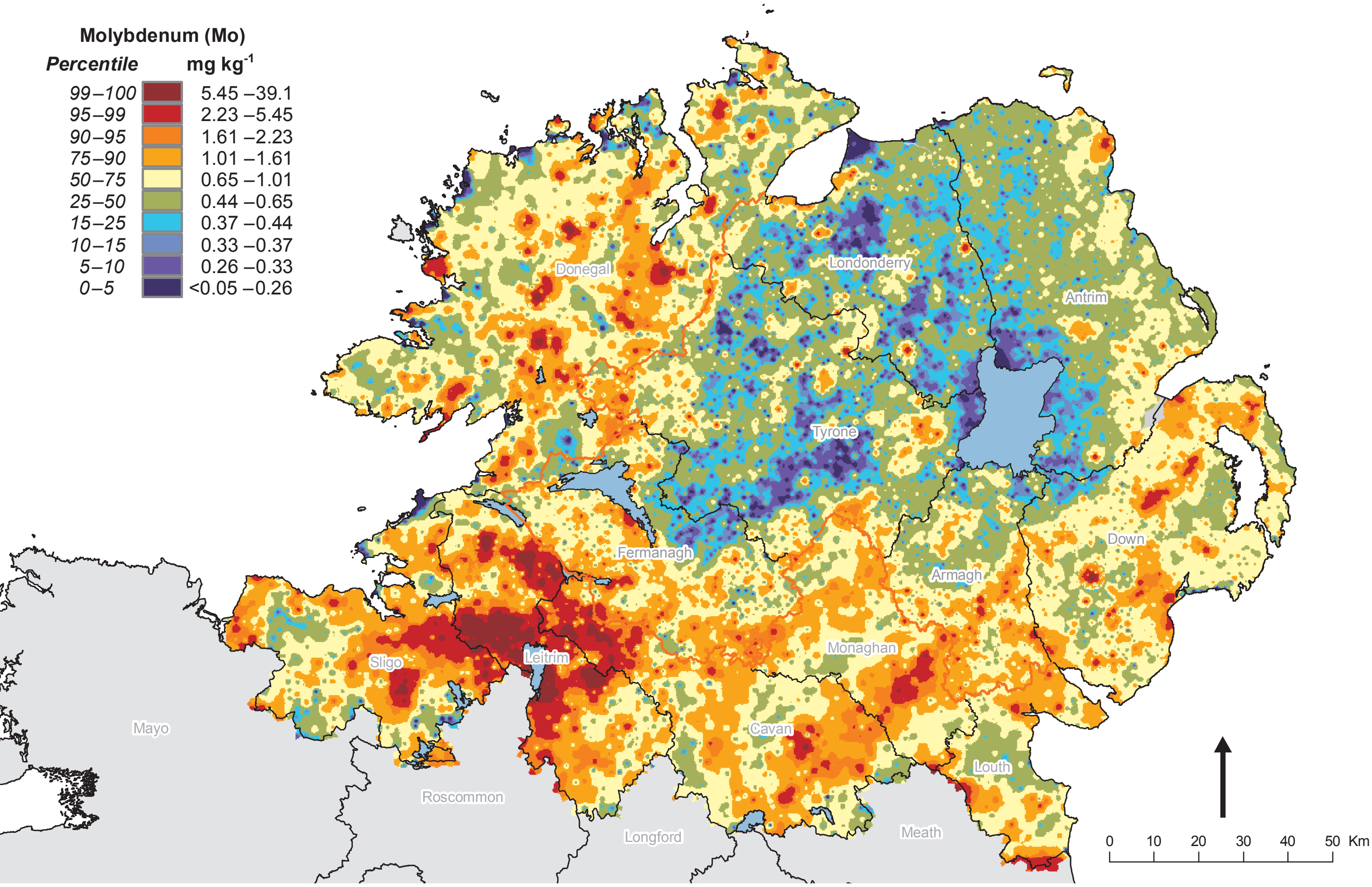

Figure 3.6. Molybdenum in 'A' soils.

light of the Tellus data and concludes that their extraction as a by-product may enhance the viability of otherwise marginal mineral deposits in the north of Ireland. In research commissioned by the Tellus Border Project, Moore *et al.* (Chapter 9, this volume) have examined the occurrences of rare earth elements (REEs) in the Mourne Mountain Complex. The granitic source and dispersion patterns of these elements and their relationship with tin and tungsten mineralisation in the Mournes have been examined. The findings will valuably inform exploration strategy for these elements elsewhere.

Agriculture

The use of geochemical data in optimising soil management in agriculture is well known and has been promoted through the soil chemistry atlases published by AFBI (Jordan *et al.*, 2000) and by Teagasc (Fay *et al.*, 2007). The more detailed sampling with a broader range of analytes of the Tellus surveys has contributed further. O'Connell (2013) described how Tellus data inform improved management of mineral imbalances that affect livestock, notably resulting in impaired reproduction, immunity to disease and structural development. Deficiencies in iodine, copper, zinc and selenium and excess of molybdenum are common in parts of Ireland and the variation in these elements in soil is evident from the Tellus soil maps (for example, Fig. 3.6). However, an 'information gap' exists between raw geochemical data and their use regionally to inform farm management decision-making,

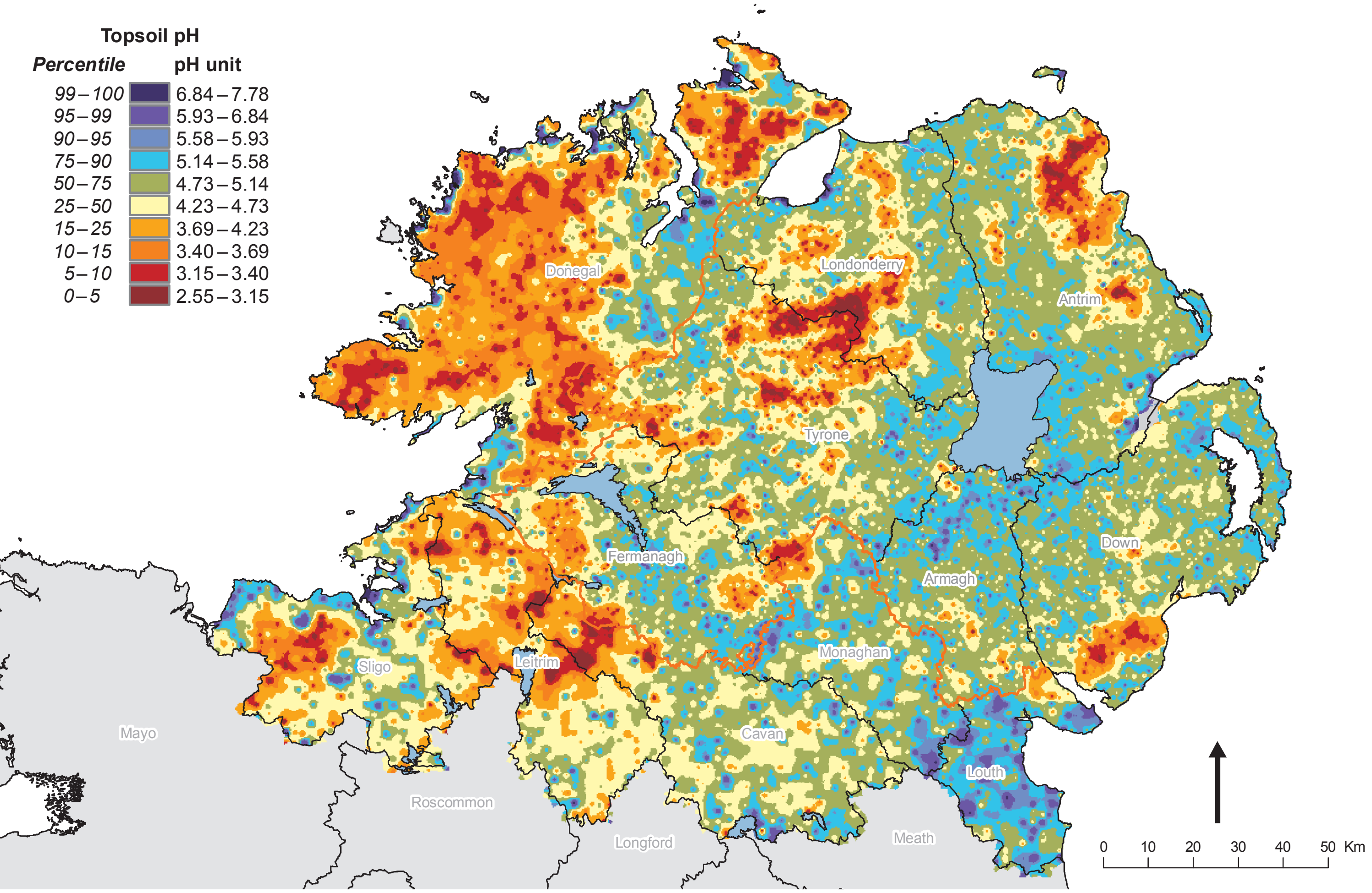

Figure 3.7. pH in 'A' soils.

agronomic advisory services and the feedstock and fertiliser industries. Studies undertaken by the BGS and GSI have attempted to address this gap (Lark *et al*., 2014 and 2016).

Smyth and Johnson (2011) used the Tellus soils data to examine the distribution of iodine in the soils of Northern Ireland. The study demonstrated the influence of non-geological sources, higher levels of iodine occurring where it is retained in soils rich in organic material and where enhanced by marine influences along the coast.

Root development and the take-up of nutrients by pasture is very dependent on the pH (acidity of soil), a parameter that varies widely across the survey area (Fig. 3.7). Take-up of the essential nutrients nitrogen, phosphorus, and potassium is low in acidic soils (low pH) but for some trace elements (manganese, copper, zinc) take-up is low in alkaline soils (high pH). Lark *et al*. (Chapter 15, this volume) analyse the statistics of the Tellus pH data and demonstrates their short-range variability; they discuss how this information can be communicated and present a means for farmers to assess the need for soil treatment locally.

Using cobalt as an example, Lark *et al.* (2014) applied existing Teagasc soil threshold values for sheep to Tellus soil geochemical maps to identify areas in the Border Region of Ireland where a cobalt deficiency in sheep is likely to occur. To address problems of uncertainty in communicating mapped results, probabilistic outputs using a verbal and numerical communication scale were developed. Opportunities exist to apply this approach to the prediction of other important micronutrients and to inform regional and farm-level land-management decisions.

Land-use management and health

Our understanding of the geochemistry of ground contamination has been broadened by research based on the Tellus data. In a study commissioned by the Tellus Border programme, Cave *et al.* (Chapter 22, this volume) use an innovative statistical approach to separate anthropogenic geochemical effects, notably from atmospheric deposition, from original terrestrial concentrations.

In another study commissioned by Tellus Border, Palumbo-Roe *et al.* (Chapter 23, this volume) used statistical analysis of stream sediment data to establish background metal concentrations in the South Armagh mining district. In such localities, there is a problem of distinguishing between anomalous populations due to the natural weathering of mineral veins and to mineral spoil. Separating these effects is important in satisfying the EU Water Framework Directive. In a previous study, Palumbo-Roe *et al.* (2014) used the data on behalf of the Northern Ireland Planning Service to assess potentially hazardous mine sites across the province.

Lass-Evans (Chapter 24, this volume) has applied a GIS-based approach to identifying varying background levels and metal anomalies in soils of the cross-border Lower Foyle catchment affected by urban and industrial activity. In an earlier study of anthropogenic contamination, Lass-Evans (2013) applied a similar approach to stream sediment data of north County Antrim, another historical mining district, to distinguish between metal concentrations from mining and from natural origins.

Accurately defining the threshold or background level of trace elements is vital both for land-use planning (in assessing possible contamination) and in agriculture (for assessing depletion of essential trace elements). The question is particularly important for parts of the Tellus and Tellus Border areas where abnormally high but naturally occurring levels of nickel, chromium and arsenic are found in soils. McIlwaine *et al.* (2014; Chapter 21, this volume) assessed the various methods of determining thresholds and examined these in the context of several metallic elements, which for geological and anthropogenic reasons are both elevated and depleted in the Tellus soils data.

A further important question in the context of human and animal health is whether or not high levels of potentially toxic elements actually find their way into the food chain. Barsby *et al.* (2012) describe the initial tests conducted on Northern Ireland soils, which indicated that the proportions of selected elements that were 'bioaccessible' varied. Cox *et al.* (2013) further examined the case of nickel and chromium in the soils over the Antrim lavas. Palmer *et al.* (Chapter 25, this volume) report on subsequent work and describe how this research informs contaminated land risk assessments.

The Tellus data have been used to research the possible links between soil geochemistry and human health, in a collaboration between Queen's University Belfast and the Northern

Ireland Cancer Registry. McKinley *et al.* (2013; Chapter 26, this volume) reported on this work, which has indicated a spatial correspondence (although not necessarily a causal relationship) between some cancers and enhanced levels of certain elements in parts of south-eastern Northern Ireland.

Environmental management and research

The importance of soils as a sink for atmospheric carbon dioxide is well known. Ashton *et al.* (Chapter 29, this volume) describe their research into how mineralogy affects the capacity of soil to concentrate carbon in four different geological settings in Northern Ireland, using the Tellus soils data as a basis for targeted sampling. They found that soils derived from basalts were likely to store greater quantities of carbon than soils from other lithologies.

In an innovative application, Rawlins *et al.* (2009) correlated the potassium signal of the airborne gamma-ray survey with loss-on-ignition from the Tellus soil geochemistry survey to improve estimation of carbon in soil.

Understanding the functioning of wetland systems is an important requirement of the Water Framework and Habitats Directives. In a research project commissioned by Tellus Border at Dundalk Institute of Technology, 'A' soils geochemistry data were used, among other data sets, to characterise wetland habitats across a range of geochemical and geological settings in the border counties (McCarthy and Rolston, Chapter 16, this volume). Flynn *et al.* (Chapter 17, this volume) also assessed how the various elements and compounds in soils, notably iron, calcium and total organic carbon, would affect the fate of undesirable nutrients entering groundwater-dependent ecosystems.

In the only study so far using the Tellus Border vegetation samples, Cullen and Fox (2013) analysed the variety of lichen and algae observed. They found a preponderance of nitrogen-tolerant varieties, reflecting high levels of airborne ammonia that is affecting local biodiversity and, perhaps, human health.

The use and limitations of soil geochemistry in forensic applications, with particular reference to the Tellus soils, are discussed by Ruffell and McKinley (Chapter 30, this volume). They conclude that these soil geochemistry data may be helpful in establishing the general provenance of forensic samples.

Conclusions

The execution of the Tellus and Tellus Border geochemical surveys, analysis and quality control benefited from the tried and tested protocols of the G-BASE programme of the BGS. The results define the geochemical baseline of some 55 elements in soils, stream sediments and stream waters. Publication of the results has stimulated unexpectedly widespread research into different aspects and applications of the data, in the fields of mineral exploration, agronomy, land-use planning, environmental management and geoforensics. Several research projects demonstrated the value of applying classical and innovative geostatistical processes to the data; these help particularly to reduce uncertainty in the data and to interpolate between widely spaced data points.

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References

Ander, L., 2013 'Waters', in M.E. Young and A.W. Donald (eds), *A Guide to the Tellus data*. Belfast. Geological Survey of Northern Ireland. Available at http://nora.nerc.ac.uk/509171/.

Appleton, J.D., Miles, J.C.H. and Young, M.E., 2011 'Comparison of Northern Ireland radon maps based on indoor radon measurements and geology with maps derived by predictive modelling of airborne radiometric and ground permeability data', *Science of the Total Environment*, 409, 1572–83. Available at http://nora.nerc.ac.uk/14598/. http://dx.doi.org/10.1016/j.scitotenv.2011.01.023.

Arthurs, J.W. and Earls, G., 2004 'Minerals', in W.I. Mitchell (ed.), *The Geology of Northern Ireland – Our Natural Foundation.* Second edition. Belfast. Geological Survey of Northern Ireland.

Barsby, A., McKinley, J.M., Ofterdinger, U., Young, M., Cave, M.R. and Wragg, J., 2012 'Bioaccessibility of trace elements in soils in Northern Ireland', *Science of the Total Environment*, 433, 398–417. Available at http://nora.nerc.ac.uk/18896/. http://dx.doi.org/10.1016/j.scitotenv.2012.05.099.

Breward, N. and Chenery, S.R., 2013 'Geochemistry of the elements', in M.E Young and A.W. Donald (eds), *A Guide to the Tellus Data*. Belfast. Geological Survey of Northern Ireland. Available at http://nora.nerc.ac.uk/509171/.

Breward, N., Stone, P., Flight, D. and Anderson, T.B., 2011 'Regional geochemical comparisons from the Lower Palaeozoic, Southern Uplands–Down–Longford terrane in Northern Ireland and Scotland', *Scottish Journal of Geology*, 47, 1, 33–43. Available at http://nora.nerc.ac.uk/15351/. http://dx.doi.org/10.1144/0036-9276/01-410.

Coulter, S. and Stinson, J., 2013 *A Preliminary Prospectivity Map for the Tellus Border Region*. Tellus Border Report. Available at http://www.tellusborder.eu/Research/.

Cox, S.F., Chelliah, M.C.M., McKinley, J.M., Palmer, S., Ofterdinger, U., Young, M.E., Cave, M.R. and Wragg, J., 2013 'The importance of solid-phase distribution on the oral bioaccessibility of Ni and Cr in soils overlying Palaeogene basalt lavas, Northern Ireland', *Environmental Geochemistry and Health*, 35, 5, 553–67. Available at http://nora.nerc.ac.uk/502771/. http://dx.doi.org/10.1007/s10653-013-9539-6.

Cullen, M.L. and Fox, H.F., 2013 *Twig Epiphyte Communities as Indicators of Environmental Quality in the Border Region of Ireland*. Tellus Border Report. Available at http://www.tellusborder.eu/Research/.

Exploration and Mining Division, 2009 *Mineral Deposits of Ireland* (map), Department of Communications, Energy and Natural Resources, Dublin. http://www.mineralsireland.ie/Publications+Archive.htm.

Fay, D., Kramers, G., Zhang, C., McGrath, D. and Grennan, E., 2007 *Soil Geochemical Atlas of Ireland*. Wexford. Teagasc and Environmental Protection Agency.

Flight, D.M.A. and Lister, T.R., 2013 'Stream sediments', in M.E. Young and A.W. Donald (eds), *A Guide to the Tellus Data*. Belfast. Geological Survey of Northern Ireland. Available at http://nora.nerc.ac.uk/509171/.

Flight, D.M.A., Lister, T.R. and Freeman, J.. 1998 *Geochemical Survey of Northern Ireland Years 1–3. Interim Report*. Keyworth, UK. British Geological Survey.

Gallagher, V., Knights, K.V., Carey, S., Glennon, M. and Scanlon, R., 2016a *Atlas of Topsoil Geochemistry of the Northern Counties of Ireland: Data from the Tellus and Tellus Border Projects*. Geological Survey of Ireland. Available at http://www.tellus.ie/about/publications/.

Gallagher, V., Knights, K.V., Carey, S., Glennon, M. and Scanlon, R., 2016b *Atlas of Stream Sediment Geochemistry of the Northern Counties of Ireland: Data from the Tellus and Tellus Border Projects*. Dublin. Geological Survey of Ireland.

Glennon, M., Harris, P., Ottesen, R.T., Scanlon, R.P. and O'Connor, P. 2014 'The Dublin SURGE Project: geochemical baseline for heavy metals in topsoils and spatial correlation with historic industry in Dublin, Ireland', *Journal of Environmental Geochemistry and Health*, 36, 2, 235–54. Special Issue on the 9th International Symposium on Environmental Geochemistry.

Johnson, C.C., Breward, N., Ander, E.L. and Ault, L., 2005 'G-BASE : baseline geochemical mapping of Great Britain and Northern Ireland', *Geochemistry: Exploration*, *Environment*, *Analysis*, 5, 4, 347–57. Available at http://nora.nerc.ac.uk/884/. http://dx.doi.org/10.1144/1467-7873/05-070.

Jordan, C., Higgins, A., Hamill, K. and Cruickshank, J.G. 2000 *The Soil Geochemical Atlas of Northern Ireland*. Belfast. Department of Agriculture and Rural Development.

Knights, K.V., 2007 *A Report on the Tellus Urban Field Campaigns of Belfast Metropolitan Areas and Londonderry, 2006*. British Geological Survey Commissioned Report 07/006N. Keyworth, UK. Available at http://nora.nerc.ac.uk/7486/.

Knights K.V., 2013a *Tellus Border Project: Quality Control and Statistical Summaries of Tellus Border Topsoil Regional Geochemical Data*, GSNI and GSI Joint Report. Available at http://www.tellusborder.eu/Library.htm.

Knights K.V., 2013b *Summary Comparison of Key Similarities and Differences between the Geochemical Survey Programmes of Tellus (NI) and Tellus Border (ROI)*. GSNI and GSI Joint Report. Available at http://www.tellusborder.eu/Library.htm.

Knights K.V., 2013c 'Tellus Border geochemistry in Ireland: new data for exploration and research applications', Tellus Border Conference, Monaghan, October 2013. Available at http://www.tellusborder.eu/Events/Results+and+Research+Conference.htm.

Knights K.V. and Glennon, M.M., 2013 *Tellus Border Project: Geochemical Data User Guide*, GSNI and GSI Joint Report. Available at http://www.tellusborder.eu/Library.htm.

Lark, R.M., Ander, E.L., Cave, M.R., Knights, K.V., Glennon, M.M. and Scanlon, R.P., 2014 'Mapping trace element deficiency by cokriging from regional geochemical soil data: a case study on cobalt for grazing sheep in Ireland', *Geoderma*, 226–227, 64–78. Available at http://nora.nerc.ac.uk/506984/. http://dx.doi.org/10.1016/j.geoderma.2014.03.002.

Lass-Evans, S., 2013 *Mining Impact on Stream Sediment Quality in County Antrim*, *Northern Ireland*, British Geological Survey Commissioned Report, CR/13/130. Keyworth, UK. Available at http://nora.nerc.ac.uk/504456/.

Lusty, P.A.J., Gunn, A.G., McDonnell, P.M., Chacksfield, B.C., Cooper, M.R. and Earls, G., 2009 'Gold potential of the Dalradian rocks of north-west Northern Ireland: prospectivity analysis using Tellus data', *Transactions of the Institution of Mining and Metallurgy (Section B Applied Earth Science)*, 118, B162–B177. Available at http://nora.nerc.ac.uk/9542/. http://dx.doi.org/10.1179/174327509X12550990457889.

Lusty, P.A.J., Scheib, C., Gunn, A.G. and Walker, A.S.D., 2012 'Reconnaissance-scale prospectivity analysis for gold mineralisation in the Southern Uplands–Down–Longford Terrane, Northern Ireland, *Natural Resources Research*, 21, 359–82. Available at http://nora.nerc.ac.uk/18864/. http://dx.doi.org/10.1007/s11053-012-9183-3.

McIlwaine, R., Cox, S.F., Doherty, R., Palmer, S., Ofterdinger, U. and McKinley, J., 2014 'Comparison of methods used to calculate typical threshold values for potentially toxic elements in soil', *Environmental Geochemistry and Health* 36, 5, 953–71.

McKinley, J. M., Ofterdinger, U., Young, M., Barsby, A. and Gavin, A., 2013 'Investigating local relationships between trace elements in soils and cancer data', *Spatial Statistics*, 5, 25–41. Available at http://nora.nerc.ac.uk/502768/. http://dx.doi.org/10.1016/j.spasta.2013.05.001.

McKinley, J.M., Deutsch, C.V., Neufeld, C., Patton, M., Cooper, M. and Young, M.E., 2014 'Use of geostatistical Bayesian updating to integrate airborne radiometrics and soil geochemistry to improve mapping for mineral exploration', *Journal of The Southern African Institute of Mining and Metallurgy*, 114, 575–86. Available at http://nora.nerc.ac.uk/509170/.

Nice, S.E., 2010 *Inorganic Soil Geochemical Baseline Data for the Urban Area of the Belfast Metropolitan Area, Northern Ireland.* British Geological Survey Open Report 08/021. Keyworth, UK. Available at http://nora.nerc.ac.uk/9599/.

O'Connell, D., 2013 'Tellus Border data and its relevance to the agricultural sector', Tellus Border Conference, Monaghan, October. Available at http://www.tellusborder.eu/Events/Results+and+Research+Conference.htm.

O'Connor, P.J., Reimann, C. and Kürzl, H., 1988 *A Geochemical Survey of Inishowen, Co. Donegal*. Geological Survey of Ireland Report Series, RS 88/1.

Palumbo-Roe, B., Linley, K., Cameron, D.G. and Mankelow, J.M., 2014. *Inventory of Closed Mine Waste Facilities in Northern Ireland. Phase II Assessment*. British Geological Survey Commercial Report CR/14/031. Keyworth, UK. Available at http://nora.nerc.ac.uk/507203/.

Rawlins, B.G., Marchant, B.P., Smyth, D., Scheib, C., Lark, R.M. and Jordan, C., 2009 'Airborne radiometric survey data and a DTM as covariates for regional scale mapping of soil organic carbon across Northern Ireland'. *European Journal of Soil Science*, 60, 1, 44–54. Available at http://nora.nerc.ac.uk/5755/. http://dx.doi.org/10.1111/j.1365-2389.2008.01092.x.

Reimann, C., Birke, M., Demetriades, A., Filzmoser, P. and O'Connor, P. (eds), 2014a *Chemistry of Europe's Agricultural Soils – Part A: Methodology and Interpretation of the GEMAS Data Set.* Geologisches Jahrbuch (Reihe B 102), Schweizerbarth, Hannover. Summary available at http://gemas.geolba.ac.at/Publications_GEMAS.htm.

Reimann, C., Birke, M., Demetriades, A., Filzmoser, P. and O'Connor, P. (eds), 2014b *Chemistry of Europe's Agricultural Soils – Part B: General Background Information and Further Analysis of the GEMAS Data Set.* Geologisches Jahrbuch (Reihe B 103), Schweizerbarth, Hannover. Summary available at http://gemas.geolba.ac.at/Publications_GEMAS.htm.

Salminen, R. (ed.), 2005 *FOREGS Geochemical Atlas of Europe. Part 1. Background Information, Methodology and Maps.* Espoo. Geological Survey of Finland.

Scanlon, R., Knights, K.V., Glennon, M.M. and O'Connor, P., 2013 'Natural and anthropogenic signatures in Irish soil: a view from the local to the continental scale', EuroGeoSurveys Workshop: Geochemical mapping of agricultural and grazing land soil in Europe (GEMAS), 5 December, FAO Headquarters, Rome. Available at http://gemas.geolba.ac.at/Download/07_Scanlon_et_al_Natural_&_anthropogenic_signatures_in_Irish_soil.ppt.

Smyth, D., 2007 *Methods Used in the Tellus Geochemical Mapping of Northern Ireland*. British Geological Survey Open Report 07/022. Keyworth, UK. Available at http://nora.nerc.ac.uk/14008/.

Smyth, D., 2013 'Soils', in M.E Young and A.W. Donald (eds), *A Guide to the Tellus Data*. Belfast. Geological Survey of Northern Ireland. Available at http://nora.nerc.ac.uk/509171/.

Smyth, D. and Johnson, C.C., 2011 'Distribution of iodine in soils of Northern Ireland, UK', *Geochemistry: Exploration, Environment, Analysis*, 11, 1, 25–39. Available at http://nora.nerc.ac.uk/14711/. http://dx.doi.org/10.1144/1467-7873/09-015.

Smyth, D. and Johnson, C., 2013 'Geochemistry: methodology', in M.E. Young and A.W. Donald (eds) *A Guide to the Tellus Data*, Geological Survey of Northern Ireland, Belfast. Available at http://nora.nerc.ac.uk/509171/.

Tóth, G., Jones, A. and Montanarella, L., 2013 'The LUCAS topsoil database and derived information on the regional variability of cropland topsoil properties in the European Union', *Environmental Monitoring and Assessment* 185, 9, 7409–25.

Webb, J.S., Nichol, I., Foster, R., Lowenstein, P.L. and Howarth, R.J., 1973 *Provisional Geochemical Atlas of Northern Ireland (Technical Communication 60).* London. Applied Geochemistry Research Group, Imperial College of Science and Technology. Available at http://www.researchgate.net/publication/265457227_Provisional_Geochemical_Atlas_of_Northern_Ireland.

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