# 25. Refining the human health risk assessment process in Northern Ireland through the use of oral bioaccessibility data

Sherry Palmer,[1] Ulrich Ofterdinger[1] and Jennifer McKinley[1]

How to cite this chapter:

Palmer, S., Ofterdinger, U. and McKinley, J.M., 2016 'Refining the human health risk assessment process in Northern Ireland through the use of oral bioaccessibility data' in M.E. Young (ed.), *Unearthed: impacts of the Tellus surveys of the north of Ireland*. Dublin. Royal Irish Academy.

DOI: https://doi.org/10.7486/DRI.9p29cr199

The Tellus geochemical surveys have identified significantly elevated concentrations of potentially toxic elements (PTEs) in rural soils from both natural sources (geogenic) and human activity (anthropogenic). In some areas PTE concentrations exceed generic soil screening criteria for assessing chronic exposure risks to human health. However, human health risk actually depends on the fraction of a contaminant that can be absorbed by the body rather than its total concentration. We assess the oral bioaccessible concentrations of arsenic, chromium, nickel and lead measured at 145 sites across Northern Ireland. Arsenic total concentrations are high over the mineralised areas of County Tyrone and County Armagh but oral bioaccessibility is highest in the latter. Total concentrations of chromium and nickel are unusually high over the north-east of Northern Ireland but bioaccessibility is lower than for arsenic; enhanced bioaccessibility of chromium and nickel occurs in parts of County Antrim and also for nickel in County Armagh. High total lead occurs throughout the surveyed area, probably with a significant anthropogenic component. Enhanced lead bioaccessibility is mapped in parts of counties Antrim and Armagh and in the vicinity of Belfast.

## Background

The starting point for assessing human health risks from exposure to land contamination is often generic soil assessment criteria such as the Soil Guideline Values (SGVs) for certain chemical elements and compounds published by the Environment Agency (EA). SGVs are intended for use during the generic quantitative risk assessment process as initial soil screening values. They are not intended for assessing the potential for acute exposure but instead are regarded as the maximum soil contaminant concentrations tolerable over an extended exposure period (EA, 2009a).

[1] Queen's University Belfast

SGVs are calculated using the contaminated land exposure assessment (CLEA) model, which assumes a default contaminant bioavailability of 100% (EA, 2009b), whereby all of an ingested contaminant will be absorbed by the body and therefore available to cause harm. However, contaminant uptake is rarely 100% of intake (Ruby *et al*., 1999). Assumptions made under such default CLEA settings can undermine the appropriateness of a CLEA-derived SGV. If required during the risk assessment process, simple or detailed adjustments can be made to the CLEA model to suit a variety of site-specific exposure situations. Detailed adjustment of the CLEA model, however, relies on specialist knowledge and the acquisition of site-specific data (EA, 2009a).

**Identifying contaminant linkages**

Different contaminants pose variable risks depending upon the exposure pathway encountered and, if available, such information is taken into account when SGVs are derived. Exceeding a SGV is not enough to conclude that significant harm will occur and it is not intended as a remediation trigger value (EA, 2009a). Neither does the presence of a high contaminant concentration in soil automatically affirm the presence of risk. Assessing potential human health risks from contaminated sites instead relies upon gathering a body of evidence to determine if risks are present through the identification of contaminant linkages, including consideration of the principal pathways of oral ingestion, dermal exposure or inhalation (DEFRA, 2012). Oral bioaccessibility data are just one piece of the puzzle when assessing exposure risks if oral exposure is a relevant risk pathway. Collation of such data supports the source–pathway–receptor model advocated in the UK CLEA framework (DEFRA and EA, 2004).

Oral bioaccessibility testing *in vitro* assists in the identification of pollutant linkages inside the human body. The oral bioaccessible fraction of a soil contaminant is the portion that is solubilised in the human digestive system and potentially available to cause adverse health effects. Bioaccessibility differs from bioavailability. For a contaminant to be bioavailable when ingested, it must cross the intestinal epithelium, be metabolised by the body, and enter the blood stream after it is rendered bioaccessible (solubilised) in the gastro-intestinal tract. Bioaccessibility is therefore the limiting step to bioavailability, as an ingested contaminant must first be bioaccessible before it can be bioavailable (Ruby *et al*., 1999). While risk assessors may be accustomed to identifying contaminant linkages in the external environment, such linkages must also exist inside the human body for health risks to be present. An internal pathway (across the intestinal epithelium) exists between the contaminant source (the soil particles) and receptor (human organs and tissues) only if soil contaminants are rendered bioaccessible in the digestive system.

Risk estimation based on the bioaccessible fraction may slightly overestimate health risks compared to the use of bioavailability data because not all soluble contaminants in the digestive system will necessarily be bioavailable. Some solubilised toxins may still be excreted by the body unabsorbed (Fig. 25.1). However, using bioaccessibility data still

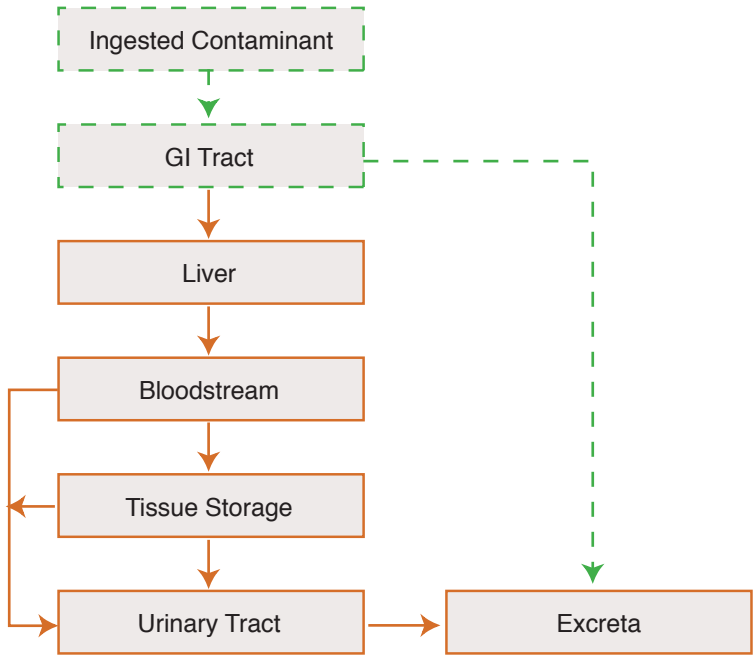


Figure 25.1. Simplified illustration of pathways an ingested contaminant could follow in the human body. Toxic health effects may occur when a toxin follows the metabolic pathway, indicated by solid lines in the diagram. Dashed lines illustrate the measured bioaccessible fraction.

provides a more accurate basis for risk assessment than the use of total soil concentrations and also supports the application of a precautionary principle to conducting a CLRA.

**The benefits of oral bioaccessibility testing**

Informed contaminated land management practices can save stakeholders substantial sums in remediation costs while also preserving soil resources. Oral bioaccessibility data supplement a lines-of-evidence approach to more accurately characterise human health risk from oral contaminant exposure. Oral bioaccessibility data are not intended for use in isolation to assess risk but instead must be interpreted with all available site-specific information, including land-use and receptor sensitivity.

Bioaccessibility data are particularly useful if the cost of *in vitro* testing will be less than the cost of site remediation. For example, oral bioaccessibility testing may have the greatest merits when applied to sites where an area of land that is too large to be remediated is classified as contaminated, particularly if there is widespread natural or diffuse anthropogenic contamination. Oral bioaccessibility data can also supplement cost-effective *in situ* remedial strategies on smaller sites and can provide the justification for the reuse of excavated material off-site.

In a case study commissioned by the Natural Environment Research Council (NERC, 2012) it was reported that an estimated £3.75 million in remediation costs were avoided during the redevelopment of a contaminated former coal mining site by employing *in vitro*

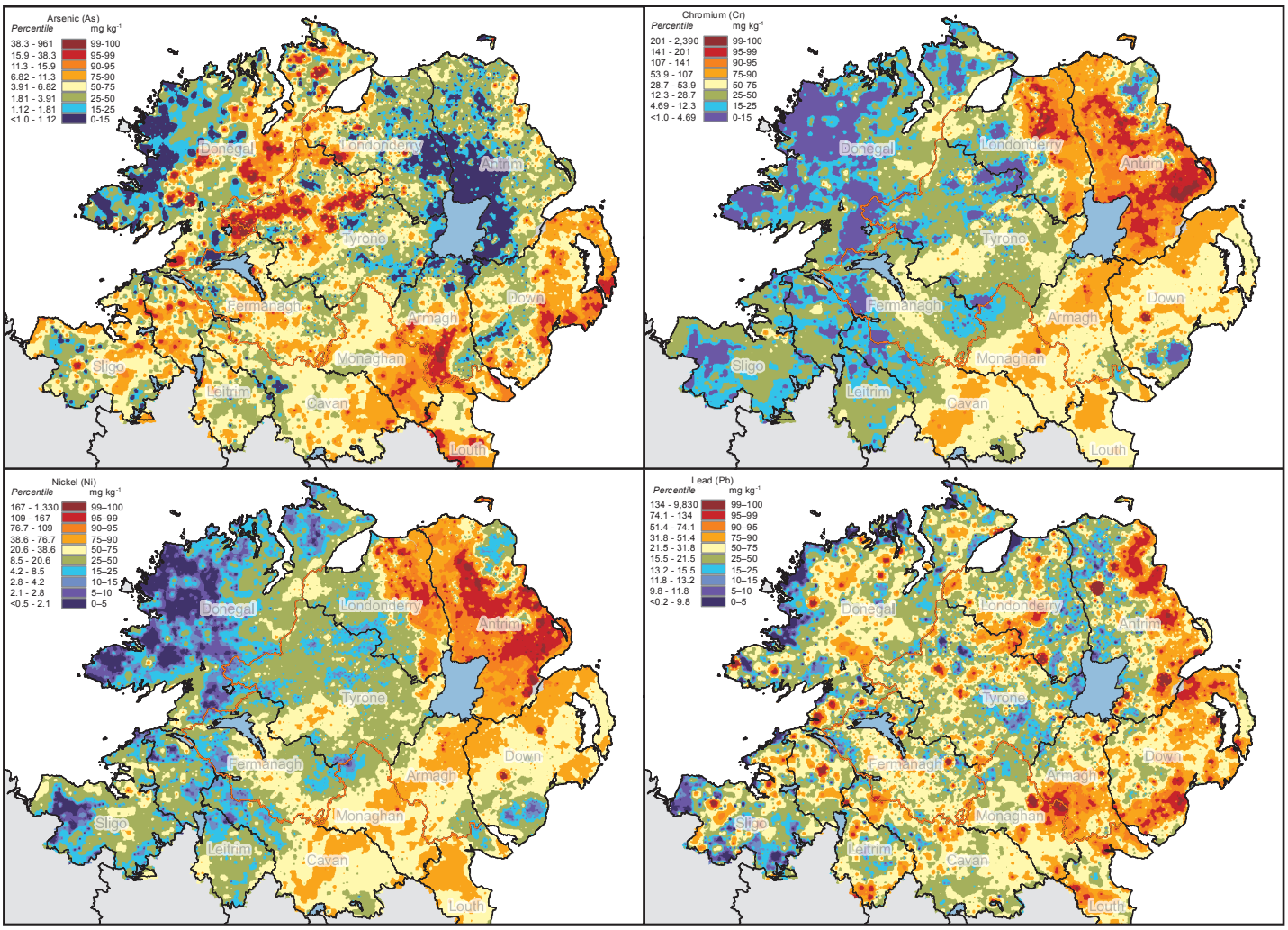


Figure 25.2. Total concentrations of As, Cr, Ni and Pb in topsoil across the Tellus and Tellus Border survey areas.

oral bioaccessibility testing during the risk assessment process. *In vitro* soil tests showed that arsenic and hydrocarbons present were not highly bioaccessible, supporting the conclusion that significant risk was not present and eliminating the need for complex remediation. On a housing development project profiled in the same NERC case study, oral bioaccessibility testing supported the conclusion that future residents would not encounter significant health risks from exposure to soil contaminants. This resulted in estimated savings of at least £7 million in remediation costs and further savings in terms of avoiding delays in development.

**Soil contamination in the north of Ireland**

Figure 25.2 shows the concentrations in topsoil of four heavy metals – arsenic (As), chromium (Cr), nickel (Ni) and lead (Pb) – over the Tellus and Tellus Border survey areas,

analysed by inductively coupled plasma mass spectrometry (ICP-MS). High total arsenic occurs in the mineralised areas of County Tyrone, extending into County Donegal, and of County Armagh, extending into counties Monaghan and Louth. High concentrations of chromium and nickel are mapped widely across the basalts of the Antrim Plateau, and from south of Lough Neagh, through County Armagh into counties Monaghan, Cavan and Louth. Total lead in topsoils displays a varied distribution throughout the Tellus and Tellus Border areas, probably reflecting its partly anthropogenic origin; like the other PTEs high lead concentrations are found in counties Armagh, Monaghan and Louth. Details of the geological provenance and geochemical characteristics of these elements are given in Young and Donald (2013).

This study examines the concentrations in Northern Ireland soils of As, Cr, Ni and Pb, which in places exceed average UK concentrations as well as generic soil screening values (Table 25.1). In an Environment Agency survey (2006) of local authorities in England and Wales, over 90% of respondents indicated that As, Ni and Pb were present at elevated levels within their jurisdictions. Such elevated concentrations resulted both from anthropogenic activity and from natural background sources (EA, 2006). Numerous sites in Northern Ireland are known to be affected by industrial contamination, although the area that could be designated as contaminated is unknown due in part to the widespread distribution in soil of naturally occurring enhanced levels of certain metals and metalloids.

**Table 25.1.** Concentrations of selected PTEs (mg $kg^{-1}$): crustal average; UK soils; Northern Ireland soils; lowest published oral exposure SGV or generic assessment criteria (GAC)

| Element | Crustal average[1] | UK average[2] | NI average[3] | NI max. | SGV or GAC[4] |
|---|---|---|---|---|---|
| As | 2–3.4 | 10.9 | 10.5 | 271.2 | 32 (inorganic) |
| Cr | 100–110 | 34.4 | 131.0 | 1229 | Cr(III): 3000 Cr(VI): 2.1 |
| Ni | 75–89 | 21.1 | 46.2 | 333.6 | 230 |
| Pb | 12–13 | 52.6 | 41.7 | 18,757 | (450) |

[1] ATSDR (2007), Garrett (2013), Taylor (1964), Lee & Yao (1970), Alloway (2013).
[2] UK Soil and Herbage Pollutant Survey (EA, 2007).
[3] Tellus Survey total XRFS concentrations in shallow soils (speciation not identified during analysis: toxic effects are species-dependent for some elements).
[4] Lowest available UK criteria reported where ingestion pathway considered relevant, assuming chronic exposure. The Pb and Ni SGVs have been withdrawn and are provided for reference only. DEFRA and EA (2002), EA (2009c, 2009d), Nathanail *et al.* (2009).

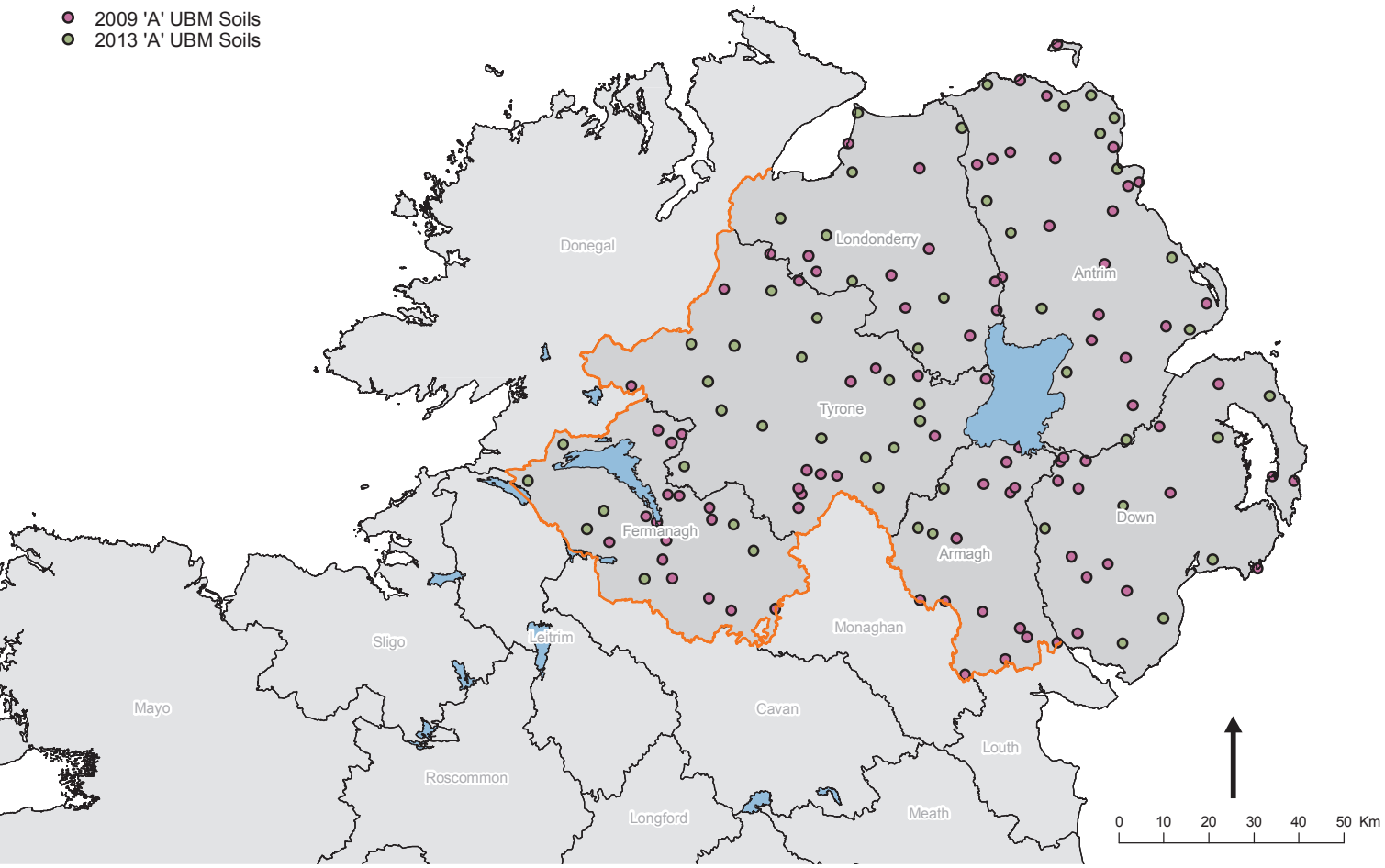


Figure 25.3. Locations of soil samples for UBM analysis.

## Methods

### Laboratory procedures

In order to determine whether oral exposure to high levels of PTEs in Northern Irish soils poses a possible human health risk, *in vitro* oral bioaccessibility testing was carried out on a subset of archived Tellus Survey shallow ('A' profile) soils in 2013 using the Unified BARGE (Bioaccessibility Research Group of Europe) Method (UBM). The UBM is an extraction technique that measures the bioaccessible portion of a toxic substance by simulating the conditions of the human stomach (gastric, G) and upper intestine (gastrointestinal, G-I) (Wragg *et al.*, 2011). The full UBM procedure is available online through the BARGE website (BARGE/INERIS, 2011).

UBM extracts were analysed by the British Geological Survey (BGS) Analytical Geochemistry Facility in Nottingham using ICP-MS to provide bioaccessible concentration data (mg $kg^{-1}$). PTE bioaccessible fractions (BAFs, %) were calculated as percentages of total and partial soil concentrations as measured by X-ray fluorescence spectrometry (XRFS) and ICP-MS respectively (Smyth, 2007). ICP-MS measures only the fraction of trace elements solubilised by *aqua regia* digestion and such analytical results are therefore often regarded as partial rather than total concentrations.

**Spatial analysis**

The UBM extraction data obtained in 2013 were amalgamated with a pre-existing UBM data set from previous analyses of Tellus soil samples in 2009 (Barsby *et al.*, 2012). A total of 145 'A' profile soil sample locations was thus considered (Fig. 25.3), covering a comprehensive geographical range of soil and underlying rock types across the study area. By joining these two UBM data sets, it was possible to develop geographical models of PTE bioaccessibility covering all of Northern Ireland.

Regional maps of As, Cr, Ni and Pb bioaccessibility were generated using inverse distance weighting (IDW) to illustrate trends in PTE bioaccessibility. IDW is an exact interpolator that estimates mapped values between sample locations by giving the greatest weight to the nearest neighbouring sample locations. For comparison against bioaccessible concentrations, total PTE concentration maps were generated from the shallow (top)soils XRFS Tellus data ($n$ = 6862) using ordinary kriging (OK) with 10–12 nearest neighbours. IDW outputs favoured the smaller sample size represented by the bioaccessibility data set while OK was well suited to providing outputs of total soil PTE concentrations for which a larger number of sample locations was available.

The extraction phase yielding the highest average bioaccessible PTE concentration was chosen for illustrative purposes in line with a precautionary principle to ensure that health risks from oral contaminant exposure were not underestimated. G concentrations are presented for Pb, Ni and Cr. In line with available validation criteria (Wragg, 2009), G-I concentrations are presented for As.

## Key findings

Table 25.2 provides summary statistics for total, partial and bioaccessible concentrations and fractions of As, Cr, Ni and Pb. For these elements, Figs 25.4–25.7 compare the spatial distributions of their total concentrations with their bioaccessibility.

**Table 25.2.** Summary statistics for As, Cr, Ni and Pb soil and bioaccessible concentrations (mg $kg^{-1}$) and fractions (BAF, %) of total XRFS and partial ICP-MS soil concentrations (Palmer *et al.*, 2014, 2015; Barsby *et al.*, 2012). Where large differences are observed between ICP-MS and XRFS concentrations and fractions, low PTE solubility is inferred, which is common for geogenic elements. SD = standard deviation.

| | | | | | XRFS | | ICP-MS | |
|---|---|---|---|---|---|---|---|---|
| **As** | Total XRFS | Partial ICP | G | G-I | G BAF | G-I BAF | G BAF | G-I BAF |
| Min. | 2.30 | 0.05 | 0.18 | 0.20 | 2.58 | 3.35 | 3.31 | 5.26 |
| Mean | 10.58 | 6.49 | 1.46 | 1.39 | 12.01 | 11.83 | 24.31 | 24.15 |
| Med. | 8.40 | 4.50 | 0.96 | 0.94 | 11.15 | 11.67 | 22.20 | 22.49 |
| Max. | 135.6 | 108.0 | 45.15 | 37.17 | 58.61 | 49.35 | 90.81 | 91.95 |
| SD | 12.09 | 10.10 | 3.83 | 3.16 | 6.73 | 5.62 | 14.20 | 13.36 |
| **Cr** | | | | | | | | |
| Min. | 4.60 | 0.50 | 0.00 | 0.00 | 0.04 | 0.00 | 0.20 | 0.02 |
| Mean | 117.4 | 39.21 | 1.50 | 1.11 | 1.20 | 1.01 | 3.67 | 3.31 |
| Med. | 85.10 | 31.00 | 1.00 | 0.82 | 1.09 | 0.89 | 3.32 | 2.81 |
| Max. | 510.2 | 180.0 | 9.96 | 7.39 | 5.36 | 4.44 | 13.04 | 19.84 |
| SD | 100.3 | 33.51 | 1.57 | 0.98 | 0.65 | 0.55 | 1.69 | 2.31 |
| **Ni** | | | | | | | | |
| Min. | 2.20 | 1.20 | 0.33 | 0.07 | 1.42 | 0.60 | 1.64 | 0.70 |
| Mean | 41.12 | 34.83 | 3.84 | 1.89 | 12.43 | 5.69 | 15.24 | 6.89 |
| Med. | 26.20 | 23.00 | 2.45 | 1.31 | 9.05 | 5.23 | 10.12 | 6.13 |
| Max. | 235.1 | 194.0 | 30.70 | 11.10 | 46.30 | 16.02 | 53.64 | 18.11 |
| SD | 42.40 | 34.47 | 4.39 | 1.86 | 9.17 | 2.84 | 11.66 | 3.57 |
| **Pb** | | | | | | | | |
| Min. | 6.00 | 5.70 | 1.49 | 0.03 | 8.22 | 0.17 | 9.69 | 0.29 |
| Mean | 40.62 | 36.04 | 15.34 | 5.96 | 32.75 | 12.46 | 38.02 | 14.43 |
| Med. | 29.20 | 24.40 | 8.38 | 3.55 | 32.51 | 12.40 | 38.48 | 14.32 |
| Max. | 291.2 | 268.0 | 199.8 | 85.90 | 68.63 | 35.06 | 74.57 | 38.08 |
| SD | 38.18 | 36.34 | 21.78 | 9.52 | 12.41 | 6.56 | 13.60 | 7.46 |

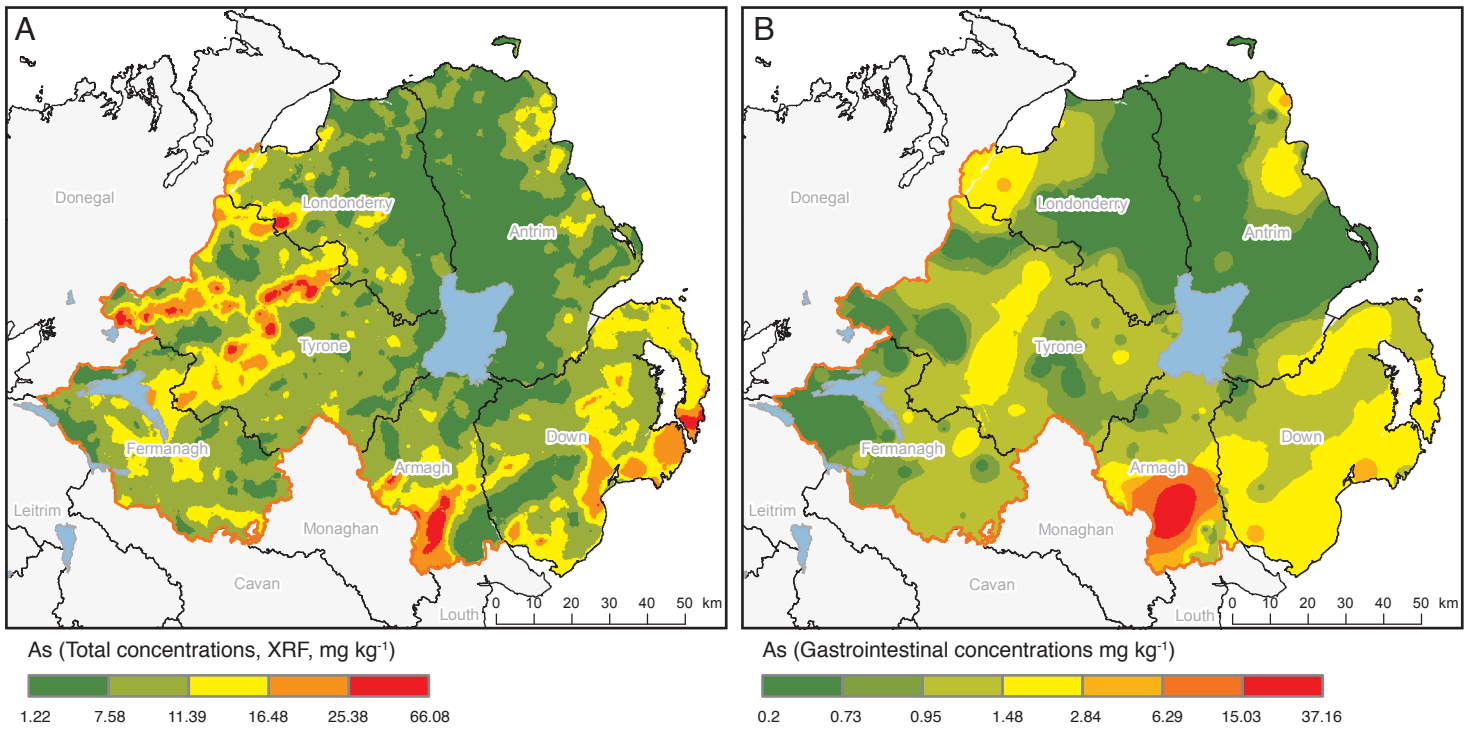


Figure 25.4. Arsenic (As) (mg $kg^{-1}$): (A) total XRFS concentrations (ordinary kriging); (B) G-I As concentrations (inverse distance weighting), showing that higher measured oral bioaccessibility spatially aligns with higher total As concentrations.

### Arsenic

On average across the study area of Northern Ireland, less than one quarter of soluble As was bioaccessible in soil (median G-I BAF = 22%). A maximum of 37 mg $kg^{-1}$ of As was solubilised by G-I UBM extraction and this maximum occurred in the central southern portion of the study area in the County Armagh mining district (Fig. 25.4b).

### Chromium

Despite high total Cr concentrations in the north-east of the study area (Fig. 25.5a), Cr displayed the lowest measured oral bioaccessibility compared with other PTEs (Table 25.2). This is likely to be due to Cr residing in insoluble forms in soil (Palmer *et al.*, 2014; Cox *et al.,* 2013). However, all exposure pathways should be investigated for this PTE as dust inhalation could also present toxic health risks to exposed populations. Furthermore, Cr speciation has not yet been analysed in Northern Ireland and toxic effects are species-dependent (Alloway, 2013). A maximum Cr G concentration approaching 10 mg $kg^{-1}$ was recorded in the north-east of Northern Ireland (Table 25.2, Fig. 25.5b).

### Nickel

Although Ni shares geogenic origins with Cr in soils of the study area, different trends in Ni oral bioaccessibility were observed. Overall, higher measured G and G-I bioaccessibility was recorded compared with Cr, although the average G fraction of total Ni concentrations reached only 12.4% (Table 25.2). Higher G Ni concentrations were found south of

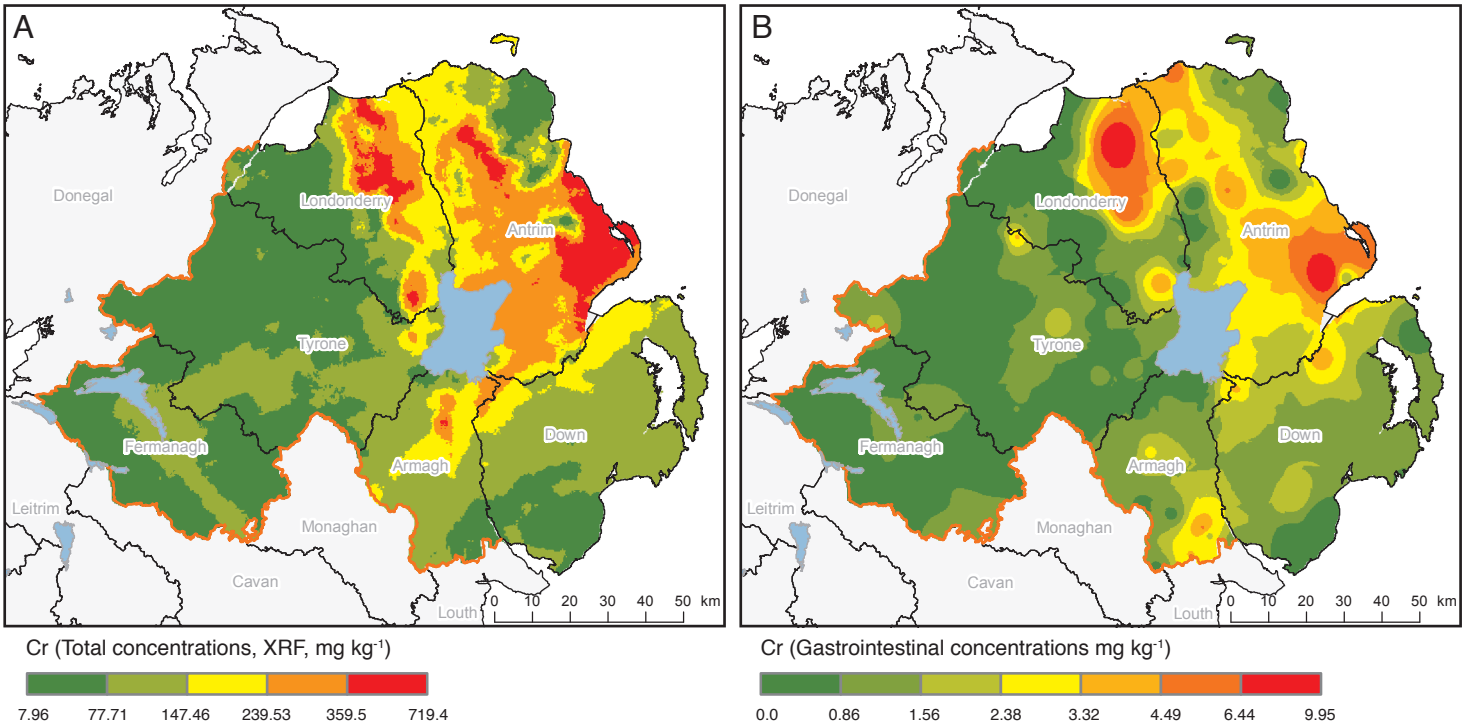


Figure 25.5. Chromium (Cr) (mg kg$^{-1}$): (A) total XRFS concentrations (ordinary kriging); (B) G Cr concentrations (inverse distance weighting), showing higher total and bioaccessible Cr concentrations in the north-east of the study area (Palmer *et al.*, 2014).

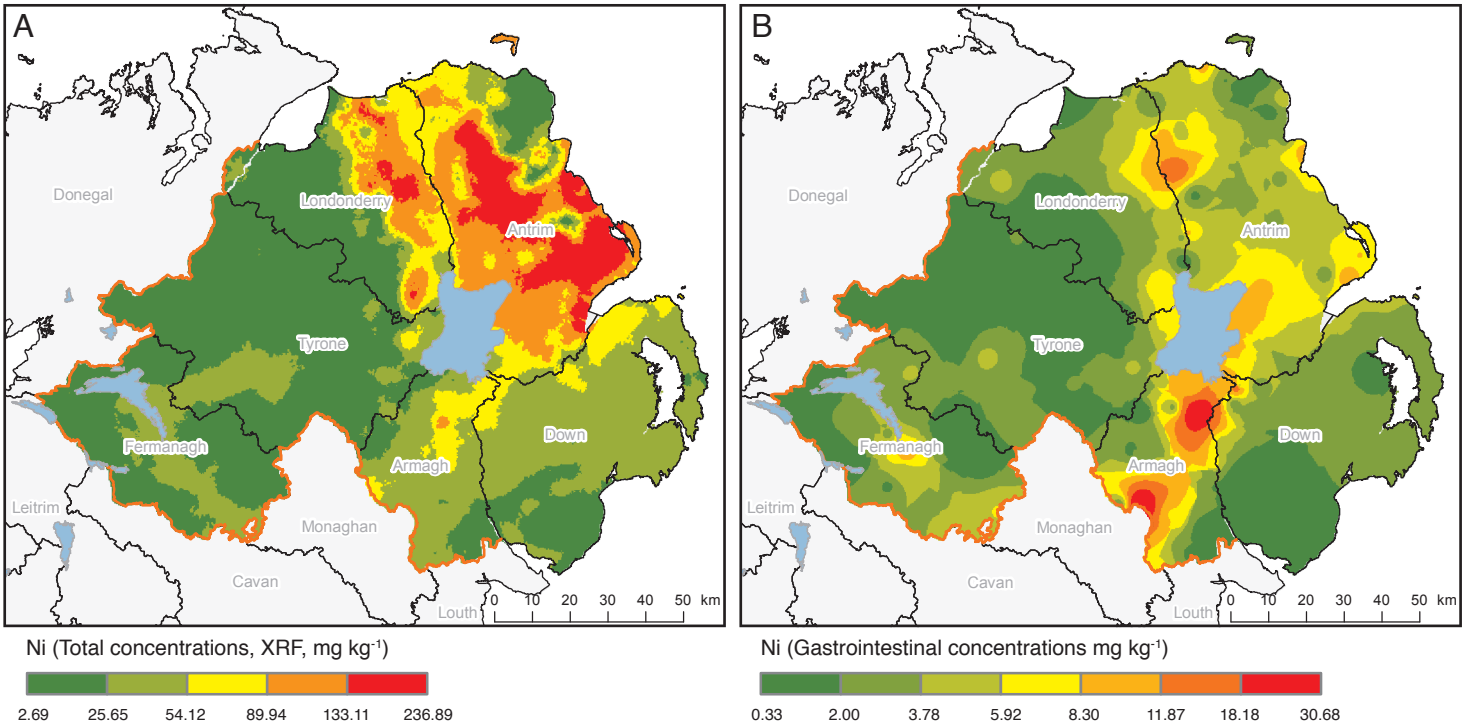


Figure 25.6. Nickel (Ni) (mg kg$^{-1}$): (A) total XRFS concentrations (ordinary kriging); (B) G Ni concentrations (inverse distance weighting), showing higher measured Ni bioaccessibility south of Lough Neagh despite the highest total Ni concentrations occurring in the north-east (Palmer *et al.*, 2014).

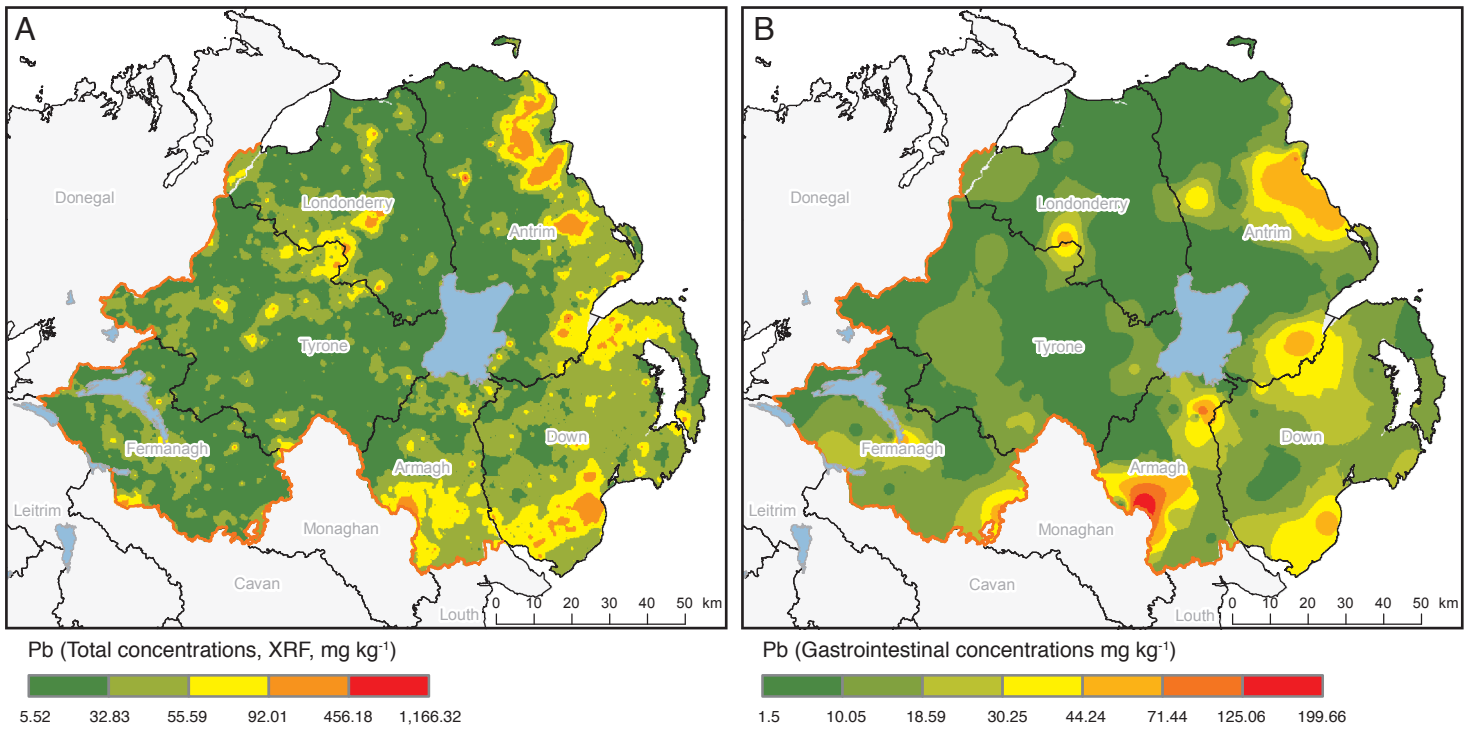


Figure 25.7. Lead (Pb) (mg $kg^{-1}$): (A) total XRFS concentrations (ordinary kriging); (B) G Pb concentrations (inverse distance weighting), showing higher total and bioaccessible Pb concentrations near urban, mined and mineralised areas (Palmer *et al.*, 2015).

Lough Neagh and in the Armagh mining district, reaching a maximum of 31 mg $kg^{-1}$, despite higher total Ni concentrations occurring in the north-east (Fig. 25.6).

### Lead

On average, approximately one third of total Pb soil concentrations were measured as bioaccessible in the stomach *in vitro*. This average decreased substantially in the intestinal phase, however, with 12.5% of total Pb potentially available for intestinal absorption.

Similarities in total and partial Pb concentrations and BAF suggest that a large proportion of Pb in the study area is highly soluble and therefore potentially bioaccessible (Table 25.2; Palmer *et al.,* 2015). Geographically, the highest concentrations of bioaccessible Pb occur along the north coast in an area of historical mining activity, around the Belfast Metropolitan Area and also in the Armagh mining district (Fig. 25.7).

## Conclusions

Conducting a thorough contaminated land risk assessment relies on the collation of data about all possible sources of and exposure pathways of toxic substances and proposed site-specific land-use activities. Here only the oral pathway has been considered. However, these results demonstrate how total concentrations of PTEs are not the sole determinant for possible human health risks from soil contaminant exposure. It is equally important to determine the fractions of PTEs in soils that are both bioaccessible and bioavailable for human absorption. These are demonstrated to be relatively low in Northern Ireland

for naturally occurring nickel and chromium, which both show unusually high total concentrations. Not all geogenic PTEs are devoid of potential health risks, however. For example, because of the documented spatial correlation between oral arsenic exposure and an increase in human disease burdens (McKinley *et al.*, 2013), further risk evaluation of this largely geogenic element may be warranted in Northern Ireland.

Elevated and bioaccessible lead concentrations appear to arise in part from anthropogenic sources, notably in the historical mining area of County Armagh, which extends into County Monaghan. Despite the low measured G-I lead fractions relative to total and partial lead concentrations measured in soils, it is arguable that any measured bioaccessible lead should be investigated, in view of the current lack of a published threshold (Palmer *et al.,* 2015).

## References

Agency for Toxic Substances and Disease Registry (ATSDR), 2007 *Toxicological Profile for Arsenic*. Atlanta, GA. United States Department of Health and Human Services. Available at www.atsdr.cdc.gov/toxprofiles/tp2.pdf.

Alloway, B.J., 2013, *Heavy Metals in Soils.* Third edition. London. Blackie Academic and Professional.

BARGE/INERIS, 2011 *UBM Procedure for the Measurement of Inorganic Contaminant Bioaccessibility from Solid Matrices*. Available at http://www.bgs.ac.uk/barge/ubm.html.

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/.

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

DEFRA, 2012 *Environmental Protection Act 1990: Part 2A. Contaminated Land Statutory Guidance*. London. The Stationery Office.

DEFRA and EA, 2002 *TOX 6: Contaminants in Soil: Collation of Toxicological Data and Intake Values for Humans – Lead*. (Withdrawn). Bristol. Environment Agency.

DEFRA and EA, 2004 *Model Procedures for the Management of Land Contamination*. Contaminated Land Report 11. Bristol. Environment Agency. Available at https://www.gov.uk/government/publications.[2]

EA, 2006 *Questionnaire Survey on the Use of In Vitro Bioaccessibility in Human Health Risk Assessment*, Science Report SC040060/SR1. Bristol. Environment Agency.

EA, 2007 *Environmental Concentrations of Heavy Metals in UK Soil and Herbage.* UK Soil and Herbage Pollutant Survey, Report No. 7. Bristol. Environment Agency.

EA, 2009a *Using Soil Guideline Values,* Science Report SC050021/SGV Introduction. Bristol. Environment Agency.

EA, 2009b *Updated Technical Background to the CLEA Model*, Science Report SC050021/SR3. Bristol. Environment Agency.

EA, 2009c *Soil Guideline Values for Inorganic Arsenic in Soil*, Science Report SC050021/Arsenic SGV. Bristol. Environment Agency.

[2] The following six entries are also available at this URL.

EA, 2009d *Soil Guideline Values for Nickel in Soil*, Science Report SC050021/Nickel SGV. (Withdrawn). Bristol. Environment Agency.

Garrett, R.G., 2013, 'Natural distribution and abundance of elements', in O. Selinus (ed.), *Essentials of Medical Geology*. Revised edition, 35–57. London. Springer.

Geological Survey of Ireland (GSI), 2013 *Tellus Border Data Viewer* (maps). Available at http://www.tellusborder.eu/Tellus+Border+Viewer.htm.

Geological Survey of Northern Ireland (GSNI), 2014 *GeoIndex: Historic Mine Workings*. Available at http://mapapps2.bgs.ac.uk/GSNI_Geoindex/ home.html.

Lee, T. and Yao, C.L., 1970 'Abundance of chemical elements in the earth's crust and its major tectonic units', *International Geology Review*, 12, 7, 778–86.

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

Nathanail, P., McCaffrey, C., Ashmore, M., Cheng, Y., Gillett, A., Ogden, R. and Scott, D., 2009 *The LQM/CIEH Generic Assessment Criteria for Human Health Risk Assessment.* Second edition. Nottingham. Land Quality Press.

Natural Environment Research Council (NERC), 2012 *Bioaccessibility Testing of Contaminated Land for Threats to Human Health*. Economic valuation report prepared for NERC by DTZ Consultancy. Available at www.bgs.ac.uk/downloads/start.cfm?id=2935.

Palmer, S., McIlwaine, R., Ofterdinger, U., Cox, S.F., McKinley, J.M., Doherty, R., Wragg, J. and Cave, M., 2015 'The effects of lead sources on oral bioaccessibility in soil and implications for contaminated land risk management', *Environmental Pollution*, 198, 3, 161–71. Available at http://nora.nerc.ac.uk/510763/. http://dx.doi.org/10.1016/j.envpol.2015.01.004.

Palmer, S., Cox, S.F., McKinley, J.M. and Ofterdinger, U., 2014 'Soil geochemical factors controlling the distribution and oral bioaccessibility of nickel, vanadium and chromium in soil', *Applied Geochemistry*, 51, 255–67.

Ruby, M.V., Schoof, R., Brattin, W., Goldade, M., Post, G., Harnois, M., *et al*., 1999 'Advances in evaluating the oral bioavailability of inorganics in soil for use in human health risk assessment', *Environmental Science and Technology*, 33, 21, 3697–706.

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

Taylor, S.R., 1964 'Abundance of chemical elements in the continental crust, a new table', *Geochimica et Cosmochimica Acta,* 28, 8, 1273–85.

Wragg, J., 2009 *BGS Guidance Material 102, Ironstone Soil, Certificate of Analysis*. Report IR/09/006. Keyworth, UK. British Geological Survey.

Wragg, J., Cave, M., Basta, N., Brandon, E., Casteel, S., Denys, S., Gron, C., Oomen, A., Reimer, K., Tack, K. and Van de Wiele, T., 2011 'An inter-laboratory trial of the unified BARGE bioaccessibility method for arsenic, cadmium and lead in soil', *Science of the Total Environment*, 409, 4016–30. Available at http://nora.nerc.ac.uk/15183/. http://dx.doi.org/10.1016/j.scitotenv.2011.05.019.

Young, M.E. and Donald, A., 2013 *A Guide to the Tellus Data*. Belfast. Geological Survey of Northern Ireland. Available at http://nora.nerc.ac.uk/509171/.

# Table of Contents:

Unearthed: impacts of the Tellus surveys of the north of Ireland
First published in 2016 by the
Royal Irish Academy
19 Dawson Street
Dublin 2
www.ria.ie



ISBN: 978-1-908996-88-6



British Library Cataloguing-in-Publication Data. A catalogue record is available from the British Library.

Design: Alex Donald, Geological Survey of Northern Ireland.
Index: Brendan O'Brien.
Printed in Poland by L&C Printing Group.