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The effect of short-range spatial variability on soil sampling uncertainty

Marcel Van der Perk [a,*], Paolo de Zorzi [b], Sabrina Barbizzi [b], Maria Belli [b], Ales Fajgelj [c], Umberto Sansone [c], Zvonka Jeran [d], Radojko Jaćimović [d]

[a] Department of Physical Geography, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands
[b] Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici (APAT), Servizio Laboratori, Misure ed Attività di Campo, Via di Castel Romano, 100–00128 Roma, Italy
[c] International Atomic Energy Agency (IAEA), Agency's Laboratories Seibersdorf, A-1400 Vienna, Austria
[d] Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

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ABSTRACT

This paper aims to quantify the soil sampling uncertainty arising from the short-range spatial variability of elemental concentrations in the topsoils of agricultural, semi-natural, and contaminated environments. For the agricultural site, the relative standard sampling uncertainty ranges between 1% and 5.5%. For the semi-natural area, the sampling uncertainties are 2–4 times larger than in the agricultural area. The contaminated site exhibited significant short-range spatial variability in elemental composition, which resulted in sampling uncertainties of 20–30%.

1. Introduction

In the recent past, it has been recognised that soil sampling operations contribute significantly to the overall quality of measurements of concentrations of substances in soil (Ramsey, 1997; Crumbling et al., 2001; de Zorzi et al., 2002; Heydorn, 2004; Kurfürst et al., 2004; Taylor et al., 2005). de Zorzi et al. (2005) defined soil sampling uncertainty as the part of the total measurement uncertainty attributable to sampling as distinct from uncertainties arising from analytical operations. There are several potential sources of sampling uncertainty. According to Gy's (1998) sampling theory of particulate material (Pitard, 1993), seven categories of sampling error can be distinguished. Table 1 lists these types of sampling error and describes how they can be reduced or avoided.

Except for the preparation error, the sampling error types are all a result of heterogeneity within the sampled lot or population, either within the primary samples (fundamental error, grouping and segregation error, increment delimitation error, and increment extraction error) or between the primary samples (long-range heterogeneity error and periodic heterogeneity error). Here, 'increment' means the individual portion of material collected by a single operation of a sampling device (de Zorzi et al., 2005). The other terms are defined in Table 1. Sampling errors at the increment level can usually be minimised by using appropriate sampling equipment and by carefully following the sampling and sample preparation protocols. This can be illustrated by the following example in which the substance under measurement is concentrated in the top few centimetres of the soil profile—as is typically the case for many fallout radionuclides. The total soil inventory, expressed as total mass or activity per unit area, is then usually estimated by sampling the topsoil to a predefined depth, for example, the top 20 cm of the soil profile. The diameter of the sampling device should be large enough to obtain a sample, which includes the largest particles, thereby minimising the fundamental error and increment delimitation error. In addition, the shape of the sampling device should ensure that the sample diameter does not change with depth (increment delimitation error). Moreover, the sampling depth should be consistent and as precise as possible to minimise the increment extraction error, although micro-topography (e.g. Borselli, 1999) often makes it hard to estimate the precise depth to which the sampling device has penetrated into the soil. For example, it can be easily shown that an error in the sampling depth of 1 cm for a total sampling depth of 20 cm causes an error of 5% in the estimated soil inventory of the substance under measurement.

Sampling errors resulting from heterogeneities between the primary samples can be reduced by choosing an adequate sampling design and by increasing the number of increments. De Gruijter et al. (2006) provide a state of the art overview of the different methods of sampling design and the corresponding estimations of the spatial mean and standard error (as a measure for the total measurement uncertainty). In addition to the estimation of the spatial mean and associated standard error, there has been a growing tendency to characterise the spatial variation of the measured soil attribute values across the area under investigation (e.g. a plot, field, or region) by means of geostatistical interpolation methods, such as kriging (see ICRU, 2006). In this case, the sample support (i.e. physical size, in terms of length, area, or volume of a sample, including its orientation) is

* Corresponding author. Fax: +31 30 2531145.
E-mail address: m.vanderperk@geo.uu.nl (M. Van der Perk).

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Table 1
Categories of sampling error according to Gy's (1998) sampling theory

Error type	Description/cause	Method of error reduction
Fundamental error	Loss of precision due to variation in particle size and composition	Increase the physical size of sample
Grouping and segregation error	Error due to distribution heterogeneities	Homogenisation
Long-range heterogeneity error	Error due to the spatial or temporal trends	Using an appropriate sampling design or increasing the number of increments
Periodic heterogeneity error	Error due to the spatial or temporal trends	Using an appropriate sampling design or increasing the number of increments
Increment delimitation error	Error due to incorrect shape of the increment	Using appropriate sampling equipment
Increment extraction error	Error due to incorrect extraction of the intended increment	Using appropriate sampling equipment and following the sampling protocols
Preparation error	Error due to loss, contamination, or alteration of the sample during preparation and transport	Using appropriate sampling equipment and following the sampling protocols

usually reduced to the size of the primary samples, although methods exist that account for the change of support (e.g. block-kriging). In the case of interpolating point measurements (point-kriging), the sampling uncertainty refers to the dispersion of the soil attribute values, which would occur if the soil were sampled repeatedly at the same location. However, because soil sampling is almost always destructive, repeated samples cannot be collected from exactly the same location. The dispersion of the soil attribute values is then largely determined by the variability at short distances (several decimetres to a few metres) from the original sampling point, which is representative of the uncertainty in locating the sampling point (Ramsey, 1997). This implies that, apart from the above sampling error types described by Gy (1998), which refer to variation within the sample, the short-range spatial variation in the close vicinity of the sampling location should also be considered as a source of uncertainty in soil sampling.

This paper aims to assess and quantify the soil sampling uncertainty arising from the short-range spatial variability of elemental concentrations in the topsoil of agricultural, semi-natural, and contaminated environments. In the framework of the SOILSAMP project coordinated by the Italian Environmental Protection Agency–APAT—three sites that are representative for these three environments were sampled using three different sampling devices at each site. Two methods to estimate the overall measurement uncertainty and the relative standard sampling uncertainty are presented. The first method is based on the variances of differences between the different sampling devices. The second method is based on the nugget variance, which is defined an apparent discontinuity at the origin of a variogram (i.e. a plot of the semi-variance of paired sample measurements as a function of distance) (see Isaak and Srivastava, 1989).

2. Methods

2.1. Sampling sites and soil sampling procedure

For this study, three sampling sites were selected: (a) a semi-natural site near Rive d'Arcano, Udine, Italy; (b) an agricultural field near Pozzuolo del Friuli, Udine, Italy; and (c) a contaminated site near Scarlino, Grosseto, Italy. All sites were sampled using the three different sampling devices according to a stratified random sampling scheme. The sampling activities were performed in different numbers of square (10 m × 10 m) grid cells (strata), depending on the size of the investigated area. Within each stratum, three nested samples—one per sampling device—were collected within at close distance to each other. To improve the estimation of short distance variation, additional clustered samples were collected within a number of randomly selected grid cells.

The agricultural field near Pozzuolo del Friuli is 1 ha in size. It had been used as arable land and has a ploughed layer of about 0.4 m. In June 2001, samples from the top 20 cm of the soil profile were collected using three sampling devices: an Edelman auger (7 cm diameter), a mechanical auger (10 cm diameter), and a shovel A. The site was dived into 100 grid cells (strata). Within the strata, the samples taken using the different sampling devices were collected within, at most, a distance of 1 m from each other. In addition, five additional samples per sampling device were collected within five randomly selected grid cells. This yielded a total number of three times 105 samples. Fig. 1a shows the spatial configuration of the sampling locations.

The semi-natural site comprised a meadow field and was sampled in October 2004. The topsoil was sampled to a depth of 20 cm using the following three sampling devices: an Edelman auger (7 cm diameter), a gouge auger (30 mm diameter), and a shovel. The field was divided into 50 grid cells (10 m × 10 m). In five randomly selected grid cells, additional samples were collected yielding a total number of 55 samples per sampling device. The samples taken by the different sampling devices were collected within 0.1–0.5 m distance of each other. Fig. 1b shows the sampling design for the semi-natural site.

The contaminated site comprised a former tailings pond near a metallurgical plant. This site was sampled in November 2002. Within a few months of the sampling, the site was remediated. The top 50 cm of the soil was sampled using a drilling corer (diameter 101 mm), a rotational corer (diameter 178 mm), and a mechanical digger (width 30 cm). The mechanical digger was used to make a trench; each primary sample was collected from one vertical side by using a shovel. The site was divided into 25 grid cells (10 m × 10 m). In 10 of randomly selected grid cells, additional samples were collected yielding a total number of 35 samples per sampling device. The samples taken by the drilling corer and the rotational corer were collected at distances of 0.2–0.5 m from each other. The samples taken by the mechanical digger were collected at the same locations as those for the rotational corer. Fig. 1c shows the sampling design for the semi-natural site.

2.2. Sample preparation and laboratory analysis

All soil samples, stored in cardboard boxes, were oven-dried at 36–40 °C. Subsequently, they were disaggregated by using a wood pestle and sieved (2 mm sieve). The fraction above 2 mm was removed and not used in the analytical phase. To obtain test samples of suitable mass, the soil samples were quartered, and finally reduced by using two riffle dividers, respectively, of 5 l and 300 ml capacity. Each test sample was milled to a particle size of less 100 μm and a test portion of between 100 and 250 mg from each test sample was put in a special plastic container for subsequent analytical operations.

The samples were analysed for arsenic (As), cobalt (Co), chromium (Cr), iron (Fe), antimony (Sb), zinc (Zn), and other elements using k0-based instrumental neutron activation analysis