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An *in situ* method for the high resolution mapping of ^{137}Cs and estimation of vertical depth penetration in a highly contaminated environment

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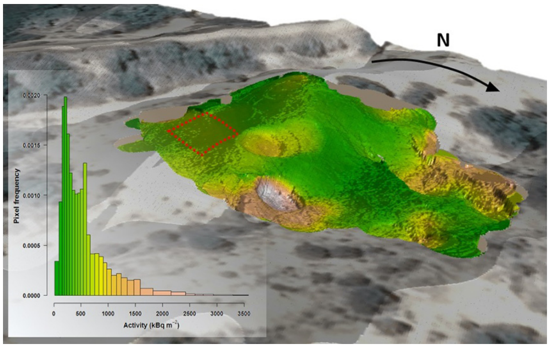
HIGHLIGHTS

- Chernobyl-derived ^{137}Cs poses a risk to human health.
- Highly heterogeneous contamination within 10 s of km difficult to characterise.
- Numerous short count time γ-ray measurements can address spatial resolution issues.
- Peak-to-valley method provides improved depth and activity estimates.

GRAPHICAL ABSTRACT



Estimated inventory and β obtained for 71 × 71 mm sodium iodide detector for Site 2 (red box) and surrounding area. Notice the reference site (red box) is significantly more stable than surrounding areas in terms of depth and activity.

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ABSTRACT

The Chernobyl nuclear power plant meltdown has to date been the single largest release of radioactivity into the environment. As a result, radioactive contamination that poses a significant threat to human health still persists across much of Europe with the highest concentrations associated with Belarus, Ukraine, and western Russia. Of the radionuclides still prevalent with these territories ^{137}Cs presents one of the most problematic remediation challenges. Principally, this is due to the localised spatial and vertical heterogeneity of contamination within the soil (~10's of meters), thus making it difficult to accurately characterise through conventional measurement techniques such as static *in situ* gamma-ray spectrometry or soil cores. Here, a practical solution has been explored, which utilises a large number of short-count time spectral measurements made using relatively inexpensive, lightweight, scintillators (sodium iodide and lanthanum bromide). This approach offers the added advantage of being able to estimate activity and burial depth of ^{137}Cs contamination in much higher spatial resolution compared to traditional approaches. During the course of this work, detectors were calibrated using the Monte Carlo Simulations and depth distribution was estimated using the peak-to-valley ratio. Activity and depth estimates were then compared to five reference sites characterised using soil cores. Estimates were in good agreement with the reference sites, differences of ~25% and ~50% in total inventory were found for the three higher and two lower activity sites, respectively. It was concluded that slightly longer count times would be required for the lower activity (<1 MBq m^{-2}) sites. Modelling and reference site results suggest little advantage would be gained through the use of the substantially more expensive lanthanum bromide detector over the sodium iodide detector. Finally, the potential of the approach was demonstrated by mapping one of the sites and its surrounding area in high spatial resolution.

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1. Introduction

The accident that occurred at the Chernobyl Nuclear Power Plant (ChNPP) in April 1986 resulted in the radioactive contamination of wide areas of Europe and, to a greater extent, the territories of Belarus, Ukraine and the western Russian Federation. In areas of south Belarus the deposition exceeded 1500 kBq/m^2 ^{137}Cs, 3 orders of magnitude greater than that which resulted from atmospheric nuclear weapons as of 1986 (UNSCEAR, 2000). As a result of the accident, a total area exceeding 60,000 km^2 of forested land was contaminated, including over 20,000 km^2 of the Gomel and Mogilev regions of Belarus in addition to areas near Kiev and in the Russian Federations' Bryansk region. The primary contaminants as a result of the accident were ^{137}Cs, ^{90}Sr, and ^{239}Pu. Highest levels of contamination, in excess of 1.4 MBq/m^2 of ^{137}Cs occur with the southernmost parts of the reserves territory over lands nearest the Chernobyl reactor while localised areas of high contamination can be found distributed throughout the reserve. Sr-90 is present at densities up to 3 MBq/m^2 while ^{241}Am levels have approximately doubled over the past twenty years and now approach 0.1 MBq/m^2 in places as a result of ingrowth from ^{241}Pu (Smith and Beresford, 2002). Actinides such as ^{238}Pu and ^{239,240}Pu are present at levels up to 0.037 MBq/m^2 and 0.074 MBq/m^2, respectively. The Polessie State Radioecology Reserve (PSRER) in southern Belarus is one of the most contaminated regions with associated total inventory estimates of 2.5 × 10^9 MBq of ^{137}Cs and 0.18 × 10^9 MBq of ^{90}Sr (Izrael and Bogdevich, 2009). Contamination is spatially highly heterogeneous over distances of 10's of meters or less while significant contamination is also found in the tree canopy and vegetation, and in aquatic systems of the area. A general overview of ^{137}Cs levels in the PSRER is presented in Fig. 1.

Cs-137 is usually considered to be the most important long-term anthropogenic contributor to the dose-levels in the environment (Miller, 2007). Its radiological prominence is due to its relatively long half-life of 32 years, its potential to be remobilised through sediment redistribution as it binds strongly to clays and its affinity to be taken in by living tissue given that it readily displaces biological potassium within the body (Povinec et al., 2003). These factors, amongst others, impart a certain emphasis on the monitoring of levels of this isotope within the environment, and such monitoring is especially important in highly contaminated areas such as those of the PSRER where considerable efforts have been expended in establishing the spatial distribution and environmental behaviour of this and other nuclides (see for example Kudelsky et al., 1996; Knatko et al., 1996; Guermentchuk et al., 1997; Sokolik et al., 2001; Yoschenko et al., 2006).

Monitoring of ^{137}Cs in soils is conventionally achieved by either of two approaches. The first consists of extracting discrete samples or cores from a site and measuring the activity of either the whole sample or of individually sliced samples representative of different depths using laboratory based gamma-ray spectrometers (Tyler, 2008). Although precise information as to the ^{137}Cs depth penetration can be obtained using this method, the resources it takes to obtain, prepare and count individual samples results in spatial coverage being limited and spatial heterogeneities may not always be captured (Tyler et al., 1996a). Estimates of ^{137}Cs penetration down the soil column are particularly important for two reasons. First, knowledge of depth distribution can contribute greatly to remediation strategies and decisions on

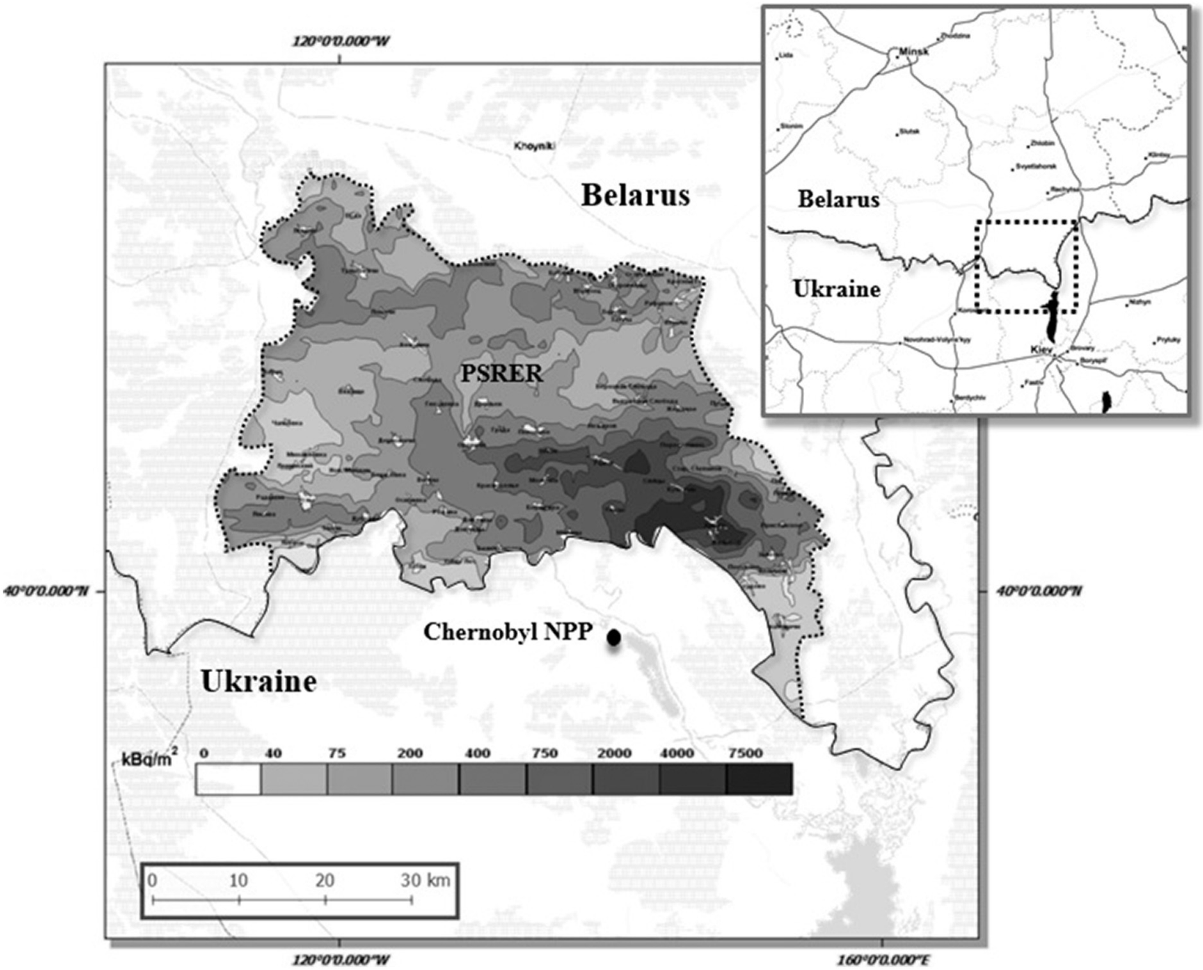

Fig. 1. Spatial distribution of the estimated ^{137}Cs inventory (kBq m^2) across the Polessie State Radioecology Reserve.