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How to make ^{137}Cs erosion estimation more useful: An uncertainty perspective

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ABSTRACT

Although the ^{137}Cs technique has been widely used to provide quantitative soil redistribution estimates since 1980s, no systematic sensitivity and uncertainty analyses have been carried out to evaluate the conversion models. The objectives of this study are to (1) perform sophisticated sensitivity and uncertainty analyses for the three widely-used models to characterize the potential sources of uncertainty including spatial variations on both reference and measuring sites and (2) explore ways to minimize uncertainty and to improve soil redistribution estimation. The normalized sensitivity showed that soil redistribution estimates were extremely sensitive to ^{137}Cs reference and sample inventories, and less sensitive, to the same degree, to bulk density, tillage depth, and particle size correction factor. Uncertainty analysis showed that the spatial variabilities on both reference and measuring sites were predominant contributors to overall uncertainty of soil erosion estimation, followed by particle size correction factor P, with negligible contributions from bulk density and tillage depth, showing that close attention must be paid to ^{137}Cs spatial variability and factor P. In the presence of substantial random spatial variation in ^{137}Cs distribution, the ^{137}Cs technique is not suitable for estimating point soil redistribution rates as is widely perceived in the literature, because part of the random variation in ^{137}Cs distribution is not a result of soil redistribution. Fortunately, the random variation can be overcome statistically by increasing independent sample numbers on both reference and measuring sites and by interpreting soil redistribution rates in terms of mean value for a uniform landform unit or contour transect (slope position) because the random errors tend to cancel out if averaged over a uniform area.

1. Introduction

The ^{137}Cs technique has been widely accepted and used in the past 40 years to estimate point soil redistribution rates (Zapata, 2010; Mabit et al., 2013). All ^{137}Cs conversion models have been developed based on the key assumption that distribution of the initial fallout ^{137}Cs is spatially uniform. However, this assumption was proven invalid (Parsons and Foster, 2011; Zhang, 2014), and the assumption violation has casted doubt upon the validity of the conventional tracing technique. It has been shown that the spatial variation of ^{137}Cs inventory on both reference and sampling sites is the major stumbling block for successful application of the tracing technique (Parsons and Foster, 2011; Kirchner, 2013; Zhang, 2014). Kirchner (2013) proposed statistical test procedures that allow discriminate soil erosion from pure spatial variation of ^{137}Cs using replicated samples from a landform element. Zhang (2014) has shown that spatial variation of ^{137}Cs inventory could be decomposed into a systematic and an intrinsic random component. The systematic component, which is caused by long-term soil erosion or sedimentation, is the true signal relating to soil redistribution. The intrinsic random component is largely caused by random spatial differences in vegetation interception, vegetation type and cover, surface residue cover, soil properties, water infiltration rates, and microtopography. Fortunately, these spatial variations are typically random in nature and thus can be resolved statistically by increasing sample number and by interpreting soil redistribution rates in terms of *mean* value for a uniform area or landform unit.

To date adequate attention has not been paid to the spatial variability of ^{137}Cs inventory on both reference and measuring sites. On reference sites, a 20% coefficient of variation (CV) of ^{137}Cs inventory was reported typical (Sutherland, 1996; Bernard et al., 1998; Basher, 2000; Fornes et al., 2005; Mabit et al., 2009). For a 20% CV, approximately 11 samples are needed to quantify the reference inventory with an allowable error of 10% at the 90% confidence. However, Sutherland (1996)

Abbreviations: CV, coefficient of variation; CI, confidence interval; SD, standard deviation; SA, sensitivity analysis; UA, uncertainty analysis; MC, Monte Carlo simulation; FAST, Fourier Amplitude Sensitivity Test; PCC, partial correlation coefficient; SRC, standardized regression coefficient; PM, proportional model; MBM1, a simple mass balance model; MBM2, an improved mass balance model; USDA-ARS, United States Department of Agriculture-Agricultural Research Service.

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reported that only one third of the studies reviewed used sufficient number of samples to determine the reference inventory, and that only 11% of the reference sites were sampled for ^{137}Cs using statistical sampling designs that allow proper variability estimation. The geostatistical analyses on spatial variability of ^{137}Cs inventories on reference sites are generally lacking in literature. For example, important relationship between sampling area (sampler size) and total sample number needed for reliable estimation of the reference mean inventory as well as the auto-correlation distance needed for independent sampling are not systematically characterized for reference sites under different land uses. It is not uncommon to take multiple cores within a relatively small reference site. If those samples are taken within the auto-correlation distance, the spatial variability will be underestimated (Kirchner, 2013). Similarly compositing several samples taken in a close vicinity of a sampling point only partially reflect the ^{137}Cs spatial variability, and thus must not be viewed as independent samples.

Compared with the intrinsic spatial variability on the reference sites, there are additional variation sources of ^{137}Cs inventory on the cultivated sites where soil erosion or sedimentation occurs. Sutherland (1994) reported that spatial variability across a gentle slope within the cultivated field was 55% greater than that within a nearby undisturbed field. Lance et al. (1986) reported that the mean variance of ^{137}Cs inventories averaged over 17 transects running along contour lines in a cultivated slope plot was 99.6 (Bq^2 core^{-2}), whereas that averaged over nine transects in an adjacent native tallgrass prairie plot was 34.8 (Bq^2 core^{-2}), showing 1.9 times increase by tillage operation and localized soil erosion. The increased variance on an eroding site would substantially reduce the sensitivity of the ^{137}Cs technique in detecting soil erosion (Kirchner, 2013). However, ^{137}Cs variability on measuring sites has seldom been considered in any systematic sensitivity and uncertainty analyses of the conversion models in literature, and let alone in the soil redistribution estimation using the technique.

Sensitivity analysis (SA) and uncertainty analysis (UA) are useful tools to understand the performance and behavior of computer models. The UA focuses on quantifying uncertainty of model output and the propagation of uncertainty from input to output. The SA provides information on how the uncertainty in the output can be apportioned to different sources of the uncertainty in the input, so that close attention can be given to the parameters or inputs that cause large uncertainty in the output. Conceptually, model uncertainty consists of two components: structural uncertainty and parametrical uncertainty. Structural uncertainty rises from generalization and simplification of complex processes in the real world, and parametrical uncertainty is the uncertainty related to parameter estimation. In general, there is a tradeoff relationship between structural and parametrical uncertainties. Increasing model complexity often improves representation of the processes under consideration; however, it inevitably increases the number of parameters and consequently uncertainty of parameter estimation. For practical applications, a balance between the two needs to be optimized so that proper models can be selected and the overall prediction uncertainty minimized for a particular application.

Though SA and UA provide useful information to model developers and users, to date only a few simple SA and UA were carried out for the conversion models of Walling et al. (2002) (Walling and He, 1999; Poreba and Bluszcz, 2008; Li et al., 2010), and more importantly none included spatial variability on measuring site as a potential source of uncertainty. Walling and He (1999) conducted a sensitivity analysis of their improved mass balance model (MBM2) with four model parameters (tillage mass depth D_m, proportion γ of the annual ^{137}Cs fallout susceptible to removal by erosion before tillage incorporation, relaxation mass depth H of the initial profile distribution of the fresh ^{137}Cs fallout, and particle size correction factor P for erosion), and reported that the estimated soil erosion rates were sensitive to all four parameters but more sensitive to D_m and P. Poreba and Bluszcz (2008) evaluated the parameter sensitivity of γ, H, P, tillage depth D_L, and bulk density B_D using assumed values for the four widely used conversion models, and reported that the normalized sensitivities for all parameters were ≤ 1. Li et al. (2010) evaluated the sensitivity of the four models of Walling et al. (2002) for a hypothetical cultivated hillslope by varying the selected model parameters by $\pm 25\%$ from the means, and concluded that both structural and parametrical uncertainties could be large under various conditions and that the four models were highly sensitive to the parameters of the ^{137}Cs reference mean, particle size correction factor P, and tillage depth D_L. Model structural uncertainty is largely unknown, and large discrepancies of soil redistribution rates often exist among the ^{137}Cs conversion models. For example, Walling and Quine (1990) demonstrated for a hypothetical site that the erosion rates estimated from a given percent depletion of ^{137}Cs could vary by more than two orders of magnitude among the 17 models tested. Such large differences clearly indicate the need for detailed model inter-comparison as well as systematic sensitivity and uncertainty analyses of the widely used models.

The objectives of this study are to (1) perform sophisticated sensitivity and uncertainty analyses for the three widely used models to characterize the potential sources of uncertainty including spatial variations on both reference and redistribution sites on an experimental plot and (2) to explore ways to minimize uncertainty and improve soil redistribution estimation using the ^{137}Cs technique.

2. Materials and methods

2.1. Site description

One experimental plot (called unit watershed) is situated on a gentle slope, which is 80-m wide and 200-m long (downslope) with a drainage area of 1.6 ha. The average slope is approximately 5% in the upper section and 1% in the lower section (Fig. 1). The plot is surrounded by earthen berms to form a watershed. An H-flume is used to measure flow levels, and a pump-type sediment auto-sampler is used to collect sediment concentration samples. Soils are primarily silt loam with an average of 23% sand and 56% silt in the tillage layer. The mean annual precipitation between 1978 and 2012 was 886 mm. The native tallgrass prairie was turned over in 1978. An annual winter wheat–summer fallow system was implemented under conventional tillage between 1978 and 1998 and under no-till afterwards. The conventional tillage included one primary till of deep moldboard plow or chisel and several passes of secondary tillage including disks and harrows in summer. No ^{137}Cs and soil losses were assumed before 1978 based on the negligible soil loss measured under the native prairie.

2.2. Sampling design

To fully capture the spatial variability, a 10-m grid was used to sample the plot area (Fig. 1). Six samples in a row were taken across the slope, and 18 rows were made downslope. To minimize border effects, a 10-m strip along the top and the two side borders was not sampled. For reference samples, a transect along a flat ridge top, which runs parallel to the top boundary of the plot, was used to ensure sufficient separations among samples. A total of 21 samples were taken at 5 to 10 m intervals along the transect. A hydraulic probe with an inner diameter of 5.2 cm was used in all samplings. The sampling depth was 30 cm, below which a preliminary study confirmed that ^{137}Cs activity was negligible.

2.3. ^{137}Cs measurement

The ^{137}Cs activity was measured by gamma spectrometry at 661.62 keV using a high-purity germanium (HPGe) coaxial detector (50% efficiency and a resolution of full width at half maximum (FWHM) of 2.2 keV at 1.3 MeV) coupled to a multi-channel analyzer. The measuring cup, made of polyethylene, is 6.5 cm tall with a uniform inner diameter of 7.0 cm. Approximately 400-g mass was used for each sample. The counting times were typically in a range of 8 to 24 h,