Nationwide soil erosion assessment in India using radioisotope tracers ^{137}Cs and ^{210}Pb: the need for fallout mapping

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Soil degradation induced by erosion represents a major threat to food production and ecosystem service globally, and in India more than 80 Mha have been impacted. In the light of the serious threat, there is a pressing need for a systematic nationwide assessment of land degradation due to erosion. We discuss the potential for using caesium-137 and lead-210 tracers to address this need and the next steps to realizing nationwide implementation.

Globally soil erosion has reached a level that endangers the sustainable supply of food for the growing global population. It already threatens food production and ecosystem service delivery and therefore, there is a pressing need to address this threat. This is especially true in India where, in a total area of 328 million hectares (Mha), 121 Mha is undergoing soil degradation, 68% of which is attributed to water erosion[1]. Water erosion rates range from 5 t ha^{-1} yr^{-1} in dense forest regions to rates in excess of 80 t ha^{-1} yr^{-1} where erosion is most severe, such as in the Shiwalik mountainous region[2]. India's average soil loss has been estimated to be 15 t ha^{-1} yr^{-1}; however, given the limited coverage of measurements, this should be treated with caution. In the light of the serious threat that soil erosion poses in the country, there is a pressing need for a systematic nationwide assessment of land degradation due to erosion using appropriate techniques. Following the approach adopted by the United States Department for Agriculture (USDA) and employed by other organizations, the majority of soil erosion studies in India have used run-off plot measurements[2]. Such studies need substantial investment (time, infrastructure and labour) to establish and maintain, as regular data collection is required for soil loss quantification. Erosion plots provide valuable insights into the role of topography, soil and vegetation, underpinning the development of widely used models such as the universal soil loss equation (USLE)[3], revised USLE (RUSLE) and modified USLE (MUSLE). Nevertheless, the understanding that can be obtained from them is constrained by scale, slope segment isolation and the range of processes that are captured. Therefore, there have been a number of critiques of the approach and an expansion in the interest in approaches that provide complementary information[4]. One approach that has attracted global attention has been the use of fallout radionuclides, including caesium-137 (^{137}Cs), lead-210 (^{210}Pb), beryllium-7 (^{7}Be) and plutonium-239 + 240 ($^{239+240}Pu$) as tracers of soil redistribution[5]. Here we discuss the importance of ^{137}Cs and ^{210}Pb as soil erosion tracers and their widespread applications[6,7].

The basis of ^{137}Cs approach to erosion assessment

^{137}Cs is an artificial radionuclide present in the environment due to human activity. The majority of ^{137}Cs fallout present in the environment was produced as a by-product of atmospheric testing of thermonuclear weapons between the 1950s and 1970s (often termed bomb-derived fallout). The maximum rate of ^{137}Cs fallout from the atmosphere occurred in 1963. Since then, there have been a number of other releases of ^{137}Cs into the environment, the most significant being as a result of accidents at the nuclear power stations at Chernobyl in 1986 and at Fukushima in 2011. ^{137}Cs released from Chernobyl is locally important, particularly in northern Europe and northern–western Eurasia, while the fallout from Fukushima was concentrated to Japan. In most parts of the world, ^{137}Cs in the environment is dominated by that derived from testing of nuclear weapons. The bomb-derived ^{137}Cs was distributed globally in the stratosphere and deposited on the earth's surface by fallout, usually in association with precipitation. After deposition of ^{137}Cs on mineral and organo-mineral soils, it was strongly and rapidly adsorbed and its subsequent redistribution has occurred in association with the erosion and deposition of soil particles by water, tillage and wind[8]. Due to the distance between India and Chernobyl and Fukushima, ^{137}Cs derived from these accidents is less important than bomb-derived fallout. ^{137}Cs has a half-life of 30.2 years and, at present about 40% of original bomb-derived fallout still remains at the undisturbed sites.

Across the globe, ^{137}Cs tracer has been used and well-studied for quantification of soil erosion and deposition by water and tillage within agricultural fields. Although the approach has come under scrutiny[9,10], it has been demonstrated to be a valuable tool in assessing long-term erosion rates. In Australia, for example, ^{137}Cs has been used in national-scale soil erosion reconnaissance that identified major soil loss (8–15 t ha^{-1} yr^{-1}) from cropping lands and quantified erosion rates for major land covers[11,12]. In land subject to shifting cultivation in North East India[13], ^{137}Cs was used to quantify much more severe erosion with rates ranging from 32 to 79 t ha^{-1} yr^{-1}. The approach has been found to be effective in a wide range of environments, including in western Turkey[14], Africa[15] and Arizona, USA[16].

The ^{137}Cs tracer allows quantification of long-term (half-century) retrospective soil erosion rates on the basis of a single field visit and subsequent sample analysis. The information gained regarding the long-term spatial pattern of soil redistribution allows study of the effect of erosion on the spatial distribution and net export of soil nutrients (e.g. carbon, nitrogen and phosphorus)[17,18], and to establish the effect of erosion on C sequestration potential within field[19–22].

The basis of ^{210}Pb approach to erosion assessment

In contrast to ^{137}Cs, ^{210}Pb is naturally occurring and fallout to the earth's surface is continuous. However, due to its strong affinity for clay and organic matter, it is also valuable as a tracer of soil redistribution[23–25]. ^{210}Pb is a naturally derived product of the ^{238}U decay series. It is present in soils as a result of two pathways: (1) *in situ* production from ^{238}U-containing minerals, via radium-226 (^{226}Ra; half-life 1622 years) and gaseous radon-222 (^{222}Rn; half-life 3.8 days) – this is termed supported ^{210}Pb; and (2) fallout from the atmosphere of ^{210}Pb derived from gaseous radon-222 that has diffused into the atmosphere from the land surface – this is termed unsupported ^{210}Pb. The supported ^{210}Pb is estimated as a function of the abundance of ^{226}Ra in the soil and porosity of the soil, which determines the loss of ^{222}Rn. The unsupported ^{210}Pb is independent of ^{226}Ra, and it is this component of ^{210}Pb that is used as an erosion tracer. As for ^{137}Cs, the inventory of unsupported ^{210}Pb measured at hillslope sites is compared with that found at non-eroded/reference site to identify erosion and deposition. Although less widely used in erosion assessment than ^{137}Cs, ^{210}Pb has been demonstrated to be an effective and complimentary erosion tracer in the UK[23], and has recently been used in conjunction with ^{137}Cs and $^{239+240}$Pu to quantify erosion in alpine agro-ecosystems of the Swiss Alps[25].

Although there is growing interest in the use of ^{210}Pb in erosion assessment, applications in Indian conditions have not been reported. ^{210}Pb has an important advantage over ^{137}Cs because it can potentially be used to quantify soil redistribution where ^{137}Cs inventories are now too low (e.g. parts of the southern hemisphere and tropics), or where inventories of ^{137}Cs have been significantly influenced by fallout sources other than bomb-derived ^{137}Cs. Nevertheless, the continuous fallout of ^{210}Pb is both an advantage and a constraint. As there is no fixed period of fallout, there is no fixed time period over which erosion-induced ^{210}Pb redistribution has taken place, and the inventory of ^{210}Pb reflects fallout over the last century. If erosion rates have been continuous over this time period, then an equilibrium model can be used to estimate them; if not, then there will be greater uncertainty in erosion rate estimation. Measurement may be difficult where ^{210}Pb detection limit is low, particularly in areas where precipitation is low. *In situ* measurement of ^{210}Pb is impossible through gamma spectrometry due to self-absorption of low-energy gamma ray (46.5 keV) in the soil. In summary, given their different properties, using both ^{210}Pb and ^{137}Cs provides the most rich and reliable information regarding soil erosion and deposition.

Common principles in erosion assessment using ^{137}Cs and ^{210}Pb

The ^{137}Cs and ^{210}Pb distributions and inventories at various landscape positions are affected by erosion and agricultural practices (mixing and translocation during cultivation; soil loss with root crop harvest; and deliberate redistribution). A rapid decrease in ^{137}Cs and ^{210}Pb content over the upper 0.2 m of the soil profile is typical of undisturbed areas and stable sites that are typically used to provide a local reference inventory (estimate of fallout input). Where cultivation is undertaken, it usually results in a relatively uniform distribution over the cultivation depth. In the absence of soil loss, the ^{137}Cs inventory is similar to local reference sites. Where net soil loss occurs, ^{137}Cs and ^{210}Pb will also be lost leading to reduced ^{137}Cs and ^{210}Pb inventories. Conversely, wherever net soil deposition takes place, there is an increase in the ^{137}Cs and ^{210}Pb inventories. This principle will be applicable to assessment of soil loss and deposition associated with sheet, rill, and tillage and wind erosion. Employing the appropriate calibration methods[7,23], it is possible to derive quantitative estimates of soil redistribution from ^{137}Cs and ^{210}Pb measurements.

Table 1. Global fallout of ^{137}Cs at different latitude bands[27,28]

Latitude band (degrees)	^{137}Cs fallout (derived from ^{90}Sr) (Bq cm^{-2})
70–80 N	0.11
60–70 N	0.28
50–60 N	0.46
40–50 N	0.52
30–40 N	0.37
20–30 N	0.28
10–20 N	0.19
0–10 N	0.13
0–10 S	0.08
10–20 S	0.07
20–30 S	0.11
30–40 S	0.12
40–50 S	0.14
50–60 S	0.08
60–70 S	0.06
70–80 S	0.04

Is a study needed across India?

Over 1000 studies using ^{137}Cs from across the globe have been published over the last four decades[6,12,13,17,18,20,26]. Nevertheless, there have been only two reported studies from India[13,21], and both are from the Himalayan region where highest fallout has occurred. In other agroclimatic regions of India, where similar erosion rates persist, no ^{137}Cs studies have been undertaken and to date no studies using ^{210}Pb for soil erosion assessment have been published.

On the basis of studies across the globe and the initial investigations in India, it would appear that the approach has merit in advancing quantitative understanding of soil redistribution and degradation. Nevertheless, there is a need to evaluate the feasibility for nationwide application by first establishing the fallout patterns of both radionuclides. On the basis of the published literature, it has been suggested that the pattern of initial ^{137}Cs fallout, associated with nuclear weapons testing, depends on latitude and annual rainfall[27,28]. Fallout over the southern hemisphere was significantly lower than in the northern hemisphere; in the latter fallout reaches a peak in the mid-latitudes and declines towards both the pole and the equator (Table 1). If this pattern persists, then ^{137}Cs fallout in southern India may be as low as 35% of the fallout in the north and this may limit the applicability of the approach in that area (8°4′ south to 37°6′ north latitude of India), and emphasizes the need to consider ^{210}Pb in this assessment. Therefore, a comprehensive study is needed to evaluate these important tracers for understanding soil redistribution. If these tracers prove applicable across India, their systematic application would address the need for a national-scale quantitative assessment of the impact of erosion-induced land degradation on food security and carbon sequestration.

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