ACTA GEOLOGICA HISPANICA, v. 35 (2000), nº 3-4, p. 197-205

Future prospects for the ^{137}Cs technique for estimating soil erosion and sedimentation rates

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ABSTRACT

Over the past five years the International Atomic Energy Agency (IAEA) has sponsored the implementation of two projects dealing with the application of the ^{137}Cs technique in soil erosion and sedimentation studies respectively. The standardisation process of the technique undertaken worldwide by 25 scientists across a wide range of environments has brought forward several new issues requiring further development. For convenience, they have been arbitrarily grouped into three main topics: a) Improvement of the ^{137}Cs technique itself, b) Potential use of other fallout radionuclides, and c) Practical applications of the technique for agricultural and environmental purposes. The overall aim of this review paper is to provide a consistent background on the important problems and limitations encountered by users of the ^{137}Cs technique as a means to contribute to its improvement. Furthermore ways/means to take advantage or greatly benefit of the technique are described for future development. Though the scientists participating in the projects mentioned above have made significant progress towards a standardised application of the ^{137}Cs technique, considerable scope remains to improve further the technique and to exploit additional applications. The IAEA through research networks and other mechanisms is promoting further applications of ^{137}Cs and other fallout radionuclides in soil erosion and sedimentation.

Key words: Soil erosion. Sedimentation. ^{137}Cs. Fallout radionuclides. Soil conservation. Erosion models.

INTRODUCTION

Soil erosion and associated sedimentation are major agricultural and environmental problems worldwide. Soil erosion causes not only on-site degradation of a non-renewable natural resource but also off-site problems such as downstream sediment deposition in fields, floodplains and water bodies. Erosion and sediment deposition are natural processes forming the landscape but they can be accelerated by human intervention, through deforestation, overgrazing and poor farming practices. In view of their great impact on sustainable agricultural production and environmental conservation there is an urgent need to assemble quantitative data on the extent, magnitude and actual rates of erosion/sedimentation as well on their economic and environmental consequences (Ritchie and Mc Henry, 1990; Walling and Quine, 1995).

The use of radionuclides in soil erosion and sedimentation research overcomes many of the limitations associated with the traditional approaches and is now being successfully applied in many developed countries. Of particular relevance is the use of fallout radionuclides in these studies (Zapata et al., 1995). Recognising this potential, the International Atomic Energy Agency (IAEA) started in 1995 the implementation of two international research networks which are termed Co-ordinated Research Projects on Soil Erosion and Sedimentation, respectively, using the ^{137}Cs and related techniques (IAEA, 1995 and 1998). The process of validation and refinement of the ^{137}Cs technique for documenting soil erosion and sedimentation undertaken by these networks comprising 25 scientists on a world-wide basis has brought forward several new issues regarding future development of these methodologies.

The purpose of this paper is to examine these issues in terms of future prospects for the application of the ^{137}Cs technique. These have been grouped into three main topics: a) Improvement of the ^{137}Cs technique, b) exploring the use of other potential fallout radionuclides, and c) exploiting the practical applications of the technique for agricultural and environmental purposes.

IMPROVEMENT OF THE ^{137}Cs TECHNIQUE

Recent advances and problems encountered in the application of the technique by the participants of the projects mentioned above are briefly described. Issues requiring further study and development are outlined.

^{137}Cs inventories

Total ^{137}Cs inputs in the soils of the study area must be sufficiently high to allow precise quantification with the available detection equipment. This is a pre-requisite for the successful application of the technique. It is therefore, important to know the global deposition pattern of ^{137}Cs in order to be able to identify countries and regions where the technique has the potential for documenting soil erosion and sedimentation.

A preliminary assessment of bomb ^{137}Cs inputs was made for 1996, based on the global deposition data for 90Sr (García Agudo, 1998). The creation of the two networks on soil erosion and sedimentation, respectively, has generated a wealth of information on the ^{137}Cs inventories for reference and eroded/depositional sites in a wide range of locations with different environments (Zapata and García Agudo, 1996 and 1998). This information is being processed and classified in a database and updated world chart of measured local ^{137}Cs inventories for future applications of the ^{137}Cs technique in other locations. It has also been suggested to develop simple models mainly based on rainfall for estimating ^{137}Cs inventories as a first approximation before starting studies with the ^{137}Cs technique in a given location.

The additional inputs of ^{137}Cs fallout to many areas of Europe that were associated with the Chernobyl accident in 1986 have complicated the interpretation of the ^{137}Cs inventories. The inclusion of several participants from Europe in the networks would provide additional information where Chernobyl fallout is relevant and the problems found to discriminate between the bomb-derived and the Chernobyl inputs. The possibility of using Chernobyl fallout for soil erosion monitoring and sedimentation studies should be explored further.

Field application

In this respect, significant progress has been made by developing standardised protocols with regard to site selection/characterisation and sampling network during the implementation of the CRP's (Pennock and Zapata, 1995; Zapata and García Agudo, 1996 and 1998). The experience gained in the application of these protocols to a wide range of environments and situations will be documented in a Manual for the field application of the ^{137}Cs technique as an output of the networks and a means for promoting the use of this technology in soil erosion and sedimentation studies. A critical factor will be the provision of guidelines for the selection of potential reference sites. Of particular interest will be cases of too low or too high ^{137}Cs inventories (Chernobyl fallout) and their implications for the application of the technique.

On the other hand, the results obtained so far in the implementation of the CRP's are being disseminated by the participating scientists through presentations in meetings, conferences, symposia, etc. and publication of scientific papers in local and international journals.

Analyses of Cs by low level gamma spectr ometry

Measurement of low concentrations of ^{137}Cs in soil/sediment samples requires the use of costly and specialised equipment and skilled staff. Also the use of standardised protocols for calibration of the equipment and analysis, and adequate quality assurance and control services are needed to obtain accurate data in soil erosion and sedimentation investigations.

An intercomparison exercise among laboratories participating in the CRP's was organised for ^{137}Cs analysis in a reference soil sample. The results of this first exercise confirmed that most participating laboratories had well-established laboratories for ^{137}Cs analysis. It was, however, recommended that further intercomparison exercises be organised to ensure the quality of the data produced. Further studies need to be conducted for the standardisation of the ^{210}Pb and ^{226}Ra analytical procedures. Assistance would be required by those laboratories involved in these measurements, most probably in the form of adequate standards for detector calibration (Zapata and García Agudo, 1998).

As a result of the long counting times required to measure the low ^{137}Cs concentrations with an appropriate accuracy, laboratories performing routine measurements need to have two or three detectors in order to achieve a reasonable sample throughput. Thus, in all these studies the main limitation is the small number of samples that can be analysed with only one detection system. Moreover, the refinement of the ^{137}Cs technique may require determination of the depth distribution of ^{137}Cs in the soil profile resulting in a larger number of samples to be analysed. In order to minimise the total number of samples required and the resulting costs, and to obtain the results in a reasonable period of time, a compromise between the number of depth increments and the available counting time needs to be reached. These considerations are one of the main limitations for the application of the ^{137}Cs technique in several developing countries, because these facilities may be available in Atomic Energy or Nuclear Physics Institutes while the scientists working in soil erosion and sedimentation are located in Agricultural/Soil Science or Hydrological Institutes. One alternative to overcome this limitation would be to contract the analytical services for ^{137}Cs in specialised laboratories with adequate capabilities to undertake these routine analyses. Another recommended strategy is the identification and upgrading of potential laboratories in each of the geographical regions of the world to increase their analytical throughput.

Modelling

Use of calibration models.

The derivation of quantitative estimates of erosion and deposition rates is dependent to a great extent on the existence of a reliable means of converting the relationship between the measured inventory at a specific sampling point and the local reference inventory to an estimate of the rate of erosion or deposition at that point. In the framework of the CRP's as a means of promoting the use of consistent and standardised calibration procedures, Walling and He (1997a) selected a number of procedures, which appear to produce meaningful results. They also produced a brochure describing the basic assumptions on the key processes involved in the ^{137}Cs distribution in the soil profile, calculation procedures involved in these models and a PC-compatible interactive software for implementing the models. No definitive guidelines for the choice of model were provided. Rather, users were encouraged to run several of the available models in order to become more familiar with their sensitivity to the input parameters, and the trade off between model complexity and the reliability and consistency of the results obtained. Participants in the CRP's have implemented the models, and exchanged experience during the co-ordination meetings. The models best suited to local conditions have been selected and some participants have undertaken further work on existing models to better adapt them to local conditions. For those working with Chernobyl fallout these inputs should be included in the mass balance models, in addition to the bomb-derived inputs.

Walling and He (1999a) have further improved and upgraded the user-friendly interactive software for estimating soil redistribution from ^{137}Cs measurements. Recently, they have also undertaken work to develop numerical procedures for estimating soil redistribution rates from ^{210}Pb measurements, particularly soil erosion rates in cultivated land. These calibration models involve different assumptions and numerical procedures (Walling and He, 1999b).

Use of spatially distributed soil erosion and sediment delivery models.

Recent advances in the development of Digital Elevation Models (DEM) and Geographical Information Systems (GIS) have promoted the application of these models at the catchment scale. Such models permit both the spatial heterogeneity of catchment land use, soil properties and topography and the spatial interaction of erosion and sediment delivery processes to be represented, and can therefore provide spatially distributed predictions of soil erosion for complex three-dimensional terrain. Spatially distributed information on soil redistribution rates is needed for validating and calibrating these distributed models in order to examine their validity at different scales and to test their functioning within a catchment, which in turn can provide the basis for further improvement. However, one important constraint in their application has been the lack of such spatially distributed information on soil redistribution rates for model validation and calibration. Rates and spatial patterns of soil erosion and sedimentation for a study area in Devon, UK, were estimated from ^{137}Cs measurements, and this information has been used for validating and calibrating topography-based distributed soil erosion and sediment delivery models, which have been incorporated into a GIS coupled to a DEM of the study area (He and Walling, 1998; Walling and He, 1998b). There is scope for standardising the use of available software for DEM.

Use of conventional erosion models.

There is a wide array of conventional models to estimate erosion/sedimentation rates such as the empirical Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), the revised USLE or RUSLE (Renard et al., 1997), and other process-based erosion models such as CREAMS (Knisel, 1980), AGNPS (Young et al., 1987), ANSWERS (Beasley et al., 1980), SEDIMOT II (Wilson et al., 1984), the Water Erosion Prediction Project model, WEPP (Laflen et al., 1991a and 1991b), the European Soil Erosion Model, EUROSEM (Morgan et al., 1992). Such models are used to make cross comparison studies of erosion rates of a particular study area and to have complementary tools for interpreting the erosion/deposition history of the study area (Elliott et al., 1991). Complementary investigations have been carried out by some participants in small catchments to improve the understanding of the erosion/sedimentation processes and influencing factors by measuring runoff and sediment discharge and estimating soil losses through the use of such conventional models. Special precautions considering the assumptions involved should be taken in making cross comparison studies of the erosion/sedimentation rates derived from ^{137}Cs measurements and conventional models.

OTHER POTENTIAL FALLOUT RADIONUCLIDES

The ^{137}Cs technique has monopolised almost all recent work in this field, and there have been few attempts to use other fallout radionuclides such as ^{210}Pb and ^{7}Be, despite increasing evidence of considerable potential for use in soil erosion investigations, both individually and as a complement to ^{137}Cs. The progress made in the standardisation of the ^{137}Cs technique is paving the way to their utilisation as described below.

Unsuppor ted ^{210}Pb

^{210}Pb is a natural product of the uranium decay series, with a half-life of 22.26 years. It is derived from the decay of gaseous ^{222}Rn, the daughter of ^{226}Ra. The isotope ^{226}Ra occurs naturally in soils and rocks and will generate ^{210}Pb, which will be in radioactive equilibrium with its parent. Diffusion of a small quantity of ^{222}Rn from the soil introduces ^{210}Pb into the atmosphere, and its subsequent fallout provides an input of this radionuclide to topsoil and sediments, which is not in equilibrium with its parent ^{226}Ra. This fallout component is called unsupported or excess ^{210}Pb, since it cannot be accounted for (or supported) by decay of the in-situ parent. The amount of unsupported lead or atmospherically derived ^{210}Pb in a sediment sample can be calculated by measuring both ^{210}Pb and ^{226}Ra and subtracting the supported or in-situ component (Appleby et al., 1986; Robbins, 1978).

As a fallout radionuclide, which is rapidly and strongly adsorbed by the surface soil, unsupported lead will behave in a similar manner to ^{137}Cs, except that its fallout input is constant through time and the supply to the soil surface is being continuously replenished. This results in slight differences in the depth distributions and the total inventories of the two radionuclides in a given study area (Walling and Quine, 1995).

Although ^{210}Pb has been widely used for dating lake sediment cores, its potential for estimating soil erosion has been essentially little exploited to date. The similar behaviour of both fallout ^{210}Pb and ^{137}Cs in soils makes it an alternative to ^{137}Cs in soil erosion investigations in areas where ^{137}Cs measurements prove to be inapplicable, for instance in areas where a significant amount of Chernobyl-derived fallout was received, or where the levels of bomb-derived ^{137}Cs fallout were too low or heterogeneous. Two approaches have been recently postulated for the conjunctive use of ^{210}Pb and ^{137}Cs in soil erosion (Wallbrink and Murray, 1996a; Walling and Quine, 1995) and sedimentation investigations (He and Walling, 1996). Further studies are required to explore the potential for using unsupported ^{210}Pb in other environments; in particular where local conditions preclude or hamper the use of the ^{137}Cs technique. Considerable scope also clearly exists for the combined use of these two fallout radionuclides for interpreting the erosion history of a study area. This work has been undertaken by several of the scientists participating in the IAEA-sponsored networks that have facilities for ^{210}Pb measurements (Zapata and García Agudo, 1996).

^{7}Be

^{7}Be is a cosmogenic radionuclide produced in the upper atmosphere by cosmic spallation of nitrogen and oxygen. The radionuclide is extremely short-lived (half-life of 53.3 days) relative to ^{137}Cs and ^{210}Pb, and consequently offers the potential for investigating soil erosion dynamics over much shorter timescales. ^{7}Be is typically concentrated in the upper 5 cm of the soil profile and it is therefore capable of providing good discrimination between sediment derived from the uppermost soil surface and that derived from depths > 10 mm, where concentrations will be effectively zero (Walling and Quine, 1995).

This radionuclide has been used in erosion plots to discriminate between sediments mobilised by sheet erosion and rill erosion, and to study the formation of rills during the course of a single simulated runoff event (Burch et al., 1988; Wallbrink and Murray, 1996b). The monitoring of the spatial distribution of the ^{7}Be activity across small plots immediately after storm events can be used to investigate local erosion patterns in response to micro-topographic controls (Walling and Quine, 1995).

There is also scope to couple measurements of ^{7}Be activity with equivalent measurements of ^{137}Cs and unsupported ^{210}Pb to provide increased capability for sediment source discrimination (Burch et al., 1988; Sogon et al., 1998).

PRACTICAL APPLICATIONS OF THE ^{137}Cs TECHNIQUE

The ^{137}Cs technique has been widely applied in a variety of locations throughout the world by several research groups to document soil erosion and sedimentation rates at the catchment scale. Such groups were comprised mainly of soil geographers, hydrologists and geomorphologists and to a lesser extent pedologists. The data obtained from these studies are important for providing guidelines for the adequate management of land and water resources at the catchment or basin scale.

Agricultur al applications

In agriculture, arable land is classified according to its suitability to sustain different types of vegetation. Accordingly, many combinations of agricultural practices may be represented within a basin or catchment, for instance cropping systems such as annual crops, fallow periods, crop rotations with variable intensity, perennial vegetation, etc.; different soil/crop management practices such as tillage, fertilisation practices, irrigation systems, etc. The degree of intensification is determined to a great extent by the predominant land tenure systems and trade agreements at the regional and national level. Specific guidelines are therefore, required at the field scale level for soil management and conservation within the basin or catchment. Thus, the ^{137}Cs technique may be applied at the field scale for determining erosion losses. This implies an adaptation of the technique to better understand the factors/processes determining soil movement and sediment storage within agricultural fields. Some participants have undertaken innovative work on the design of sampling strategies and sample collection/processing, considering the pedological units along the landscape or topo-sequences and land use/tillage systems, in order to optimise the technique and make it more cost-effective for agronomic purposes. From this work it is expected to facilitate the sampling processes while maintaining the accuracy of the results. These studies also include the corresponding refinement of the calibration models and related software. Attempts to calibrate the input parameters should be made only after analysing the factors affecting the lack of accuracy of the results.

The ^{137}Cs redistribution data have been used to provide the landscape-scale framework for research into the erosion-productivity relationship (Pennock and de Jong, 1987; Pennock et al., 1994). These studies focused on soil redistribution, as determined by the ^{137}Cs data, and its effects on soil quality parameters and crop yields. The results demonstrated a clear relationship between the shape and substance of the land surface and soil redistribution. Although the link between soil redistribution and changes in soil quality was well documented in the study area (Southern Saskatchewan), the impact of these changes in soil quality on production remained less clear.

These changes can be better studied on a long-term basis through the use of models such as a decision support tool for environmental management (Pierce, 1991). One such widely-applied model is the Environmental Policy Integrated Climate (EPIC), which is a comprehensive model encompassing weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics and plant environment control (Williams, 1995). The EPIC model has been frequently updated through accumulated experience and user demand. There is potential to test EPIC's aptitude to estimate erosion/sedimentation and its relationship to crop yields (Izaurralde et al., 1996; Roloff et al., 1998).

Further investigations are also needed to establish adequate relationships between land use/management including soil characteristics and their position, shape, gradient and orientation in the landscape and the estimated erosion losses, in order to provide guidelines for soil conservation measures. These studies are difficult because of the interaction of multiple factors that influence the erosion rates as well the soil components that affect productivity (Bruce et al., 1995). These factors form a complex and interdependent system. Models are used to establish a perspective of the interdependence of the various factors associated with the ecological effects of soil erosion (Pierce, 1991; Pimentel et al., 1995). On the other hand the erosion estimates from ^{137}Cs measurements represent medium-term-integrated values over time and space.

Reliable and proven soil conservation technologies include ridge planting, minimum/conservation tillage, crop rotations, strip cropping, grass strips, mulches, contour planting, cover crops, and border plot fences. Although the specific mechanisms involved vary, all conservation methods reduce erosion rates by maintaining a protective cover over the soil, which is often accompanied by a reduction in tillage intensity. Each conservation technology may be used separately or in combination with other erosion control measures. It is reported that the implementation of appropriate soil and water conservation practices has the potential to reduce erosion rates from 2 to 1000-fold and water loss from 1.3 to 21.7 fold (Pimentel et al., 1995). It is therefore, highly relevant to evaluate the combined effect of these practices at the field scale level in cultivated areas. Participants of the CRP's have realised the potential of the erosion data from ^{137}Cs measurements and have started to evaluate land use/management systems in agricultural fields.

Another innovative approach in the application of the technique is to assess erosion in long-term experiments investigating sustainable agricultural production systems. Measuring the current pattern of soil erosion in test fields and relating these patterns to differences in productivity does this. If the measurements are repeated in 7 to 10 years and the pattern of soil erosion is again established, it will be possible to determine if the patterns of change in soil erosion can be related to the different agricultural practices utilised (Ritchie, 1995).

Environmental applications

Erosion not only damages agricultural land but also negatively affects the surrounding environment. It is therefore important to consider the off-site effects of soil erosion in the study area. Such off-site problems may include roadway, sewer and basement siltation, drainage disruption, undermining of foundations and pavements, gullying of roads, earth dam failures, eutrophication of waterways, siltation of harbours and channels, loss of reservoir storage capacity, loss of wildlife habitat, disruption of stream ecology, flooding, poor water quality, damage to public health and increased water treatment costs (Clark et al., 1985). The main off-site damage is caused by soil particles leaving the fields and entering into the water systems. The sediments that are deposited in streams and rivers harm aquatic plants and other organisms by contaminating the water with fertiliser and pesticide chemicals or radionuclides in some areas, all of which ultimately affect habitat quality.

There is considerable potential for extending the use of ^{137}Cs as a sediment tracer from consideration of soil redistribution within individual fields to investigations of the movement and storage of sediment within a drainage basin (Campbell, 1983; Walling and Bradley, 1988).

Walling and Bradley (1989) have demonstrated how ^{137}Cs measurements can provide the basis for establishing the sediment budget for a small drainage basin. The technique has been successfully applied in fingerprinting suspended sediment sources and estimating rates of overbank sediment deposition in river floodplains (Walling and Woodward, 1992; Walling et al., 1993; Walling and He, 1997b, 1998a).

Participants in the CRP have realised this potential and have used the spatial pattern of erosion and deposition in the study areas to document the spatial distribution of contaminants such as radionuclides in the Chernobyl-affected area, and residues of agrochemicals (fertilisers and pesticides) in intensively cultivated areas.

Siltation is a major problem in reservoirs because it reduces water storage and electricity production and shortens the lifetime and increases the maintenance cost of dams. In view of its great economic and environmental impact to developing countries, the IAEA is launching a project on Dam Safety and Sustainability to be implemented under the Technical Co-operation Programme.

Socio-economic studies

Data of erosion /sedimentation rates are needed for estimating the economic costs of soil loss and degradation and off-site effects. These costs in turn are included in the cost/benefit analysis of the agricultural system under study (Murdock et al., 1980). Conservative estimates of these costs made in the USA clearly demonstrated that it makes sound economic sense to invest in programs that are effective in controlling erosion (Pimentel et al., 1995). Few economic studies of the erosion costs exist and there is considerable scope for utilising the erosion/sedimentation rates from the ^{137}Cs measurements for the economic evaluation of a soil conservation program in a catchment or basin.

In addition, data obtained at the field level are also useful to determine the most advantageous combination of appropriate soil and water conservation technologies. This selection should be based not only upon technical parameters (soil, climate, topography, vegetation cover, etc.) but also socio-economic considerations of the local inhabitants.

CONCLUSION

The ^{137}Cs technique offers an effective and valuable means for studying rates and patterns of soil redistribution at the watershed level. The successful application of the technique by the scientists participating in two IAEA sponsored networks has generated an important source of erosion/sedimentation data across a wide of environments. Though significant progress has been made towards the standardised application of the technique, considerable scope remains to improve further the technique and to explore additional applications. Through research networks and other mechanisms, IAEA is promoting further applications of fallout radionuclides in soil erosion and sedimentation studies.

ACKNOWLEDGEMENTS

The studies reported are carried out in the frame of the Coordinated Research Projects on Soil Erosion (D1.50.05) and Sedimentation (F3.10.01) as part of the Research Contract Programme of the International Atomic Energy Agency. The authors are grateful to Dr. Phil M. Chalk and to anonymous referees for his useful comments on the manuscript.

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