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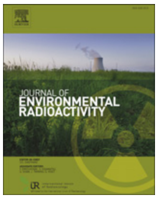

Review

Fallout radionuclide-based techniques for assessing the impact of soil conservation measures on erosion control and soil quality: an overview of the main lessons learnt under an FAO/IAEA Coordinated Research Project

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ABSTRACT

This paper summarizes key findings and identifies the main lessons learnt from a 5-year (2002–2008) coordinated research project (CRP) on "Assessing the effectiveness of soil conservation measures for sustainable watershed management and crop production using fallout radionuclides" (D1.50.08), organized and funded by the International Atomic Energy Agency through the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. The project brought together nineteen participants, from Australia, Austria, Brazil, Canada, Chile, China, Japan, Morocco, Pakistan, Poland, Romania, Russian Federation, Turkey, United Kingdom, United States of America and Vietnam, involved in the use of nuclear techniques *and, more particularly*, fallout radionuclides (FRN) to assess the relative impacts of different soil conservation measures on soil erosion and land productivity. The overall objective of the CRP was to develop improved land use and management strategies for sustainable watershed management through effective soil erosion control practices, by the use of ^{137}Cs (half-life of 30.2 years), ^{210}Pb$_{ex}$ (half-life of 22.3 years) and ^{7}Be (half-life of 53.4 days) for measuring soil erosion over several spatial and temporal scales.

The environmental conditions under which the different research teams applied the tools based on the use of fallout radionuclides varied considerably – a variety of climates, soils, topographies and land uses. Nevertheless, the achievements of the CRP, as reflected in this overview paper, demonstrate that fallout

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radionuclide-based techniques are powerful tools to assess soil erosion/deposition at several spatial and temporal scales in a wide range of environments, and *offer potential* to monitor soil quality. The success of the CRP has stimulated an interest in many IAEA Member States in the use of these methodologies to identify factors and practices that can enhance sustainable agriculture and minimize land degradation.

1. Introduction

The present world population of 6 billion is expected to reach 9.3 billion by the year 2050. Against a background of increased population growth and pressure on the availability of land and water resources worldwide several countries will face major challenges to achieve food security in a sustainable manner due to their low available per capita land area, scarcity of fresh water resources and inadequate infrastructure. This is further compounded by severe soil degradation, particularly in Sub-Saharan Africa and South Asia, leading to increased risks of soil erosion. The global extent of land degradation is estimated about 1.9 billion ha. It is anticipated that as climate change develops an increase in the incidences of extreme weather events such as storms, droughts and floods will occur, increasing further the risks of land degradation and soil erosion.

Soil erosion and associated soil redistribution driven by water and wind are natural processes that can be accelerated by anthropic activities, such as land use change, farm mismanagement, deforestation and overgrazing. These processes cause not only on-site soil losses affecting crop productivity (Dercon et al., 2003, 2006; Schmitter et al., 2010), but also off-site problems of mobilization and transport of sediment and associated contaminants that can find their way into dam/reservoirs and water bodies. Tillage erosion, the progressive downslope movement of soil by tillage, is a separate form of erosion which can cause soil loss and accumulation within fields and can further increase wind and water erosion (Dercon et al., 2007; Li et al., 2008a,b). While soil erosion is the predominant land degradation process occurring worldwide, more than three quarters of the total area of agricultural land area affected by erosion is situated in the developing countries of Africa, Asia and Latin America. Worldwide, more than 75% of the soil losses come from agricultural land. Global estimates of the cost of such losses are of the order of US $400 billion per year (1992 US dollars) (Pimentel et al., 1995; Lal, 2006).

In view of the above, there is an urgent need to obtain reliable quantitative data on the extent and rates of soil erosion/redistribution, to provide a more comprehensive analysis of the problems and to underpin soil conservation and sediment control strategies, including the assessment of their economic and environmental impacts (Stroosnijder, 2005; Boardman, 2006). The quest for alternative rapid and cost-effective techniques for assessing soil erosion to complement classical methods has directed attention to the use of fallout radionuclides (FRN), particularly caesium-137 (^{137}Cs), as tracers to obtain quantitative estimates of soil erosion and deposition on agricultural landscapes (Ritchie and McHenry, 1990).

The global fallout input of ^{137}Cs from the atmosphere to the land surface occurred through wet (rainfall) in the 1950s and 1960s, due to the testing of atomic weapons (bomb fallout). The spatial distribution of ^{137}Cs fallout shows a clear latitudinal zoning, with total fallout in the northern hemisphere being substantially larger than in the southern hemisphere. The ^{137}Cs inventories in the southern hemisphere are, however, still measurable using appropriate detectors and counting times. This global pattern is further complicated by fallout ^{137}Cs originating from the Chernobyl accident, which increased the existing bomb-derived inventories by several orders of magnitude in some locations in Europe. At the local scale, however, the total ^{137}Cs fallout can generally be assumed to be uniform, at least at a scale where longer-term (50 year) rainfall can also be considered uniform.

Once ^{137}Cs is deposited, it is rapidly and strongly adsorbed by fine soil particles (clay and humus) and accumulates at or near the soil surface. Documenting the subsequent redistribution of the FRN tracers, as they move across the landscape in association with soil or sediment particles, primarily through physical processes, affords a very effective tool for measuring erosion and deposition by water, wind and tillage within agricultural landscapes (Mabit et al., 2008a; Zapata and Nguyen, 2010). The resultant soil redistribution data (soil and sedimentation rates and patterns) represent an integrated measurement of all processes leading to soil redistribution and occurring during the period extending from the time of the main fallout input to the time of sampling.

The Soil and Water Management & Crop Nutrition Subprogramme of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture assists Member States to use isotopic and nuclear-based techniques to diagnose constraints and pilot-test interventions to intensify crop production in a sustainable manner through the integrated management of soil, water and nutrient resources without land degradation. This objective is pursued through a range of activities including (a) Coordinated Research Projects (CRP) which involve international networks of national agricultural research organizations from developing countries and advanced research organizations, and (b) Technical Cooperation Projects (TCP) that promote technology transfer through technical support and institutional capacity building in Member States.

A recent IAEA Coordinated Research Project (CRP), which provides the focus of this paper, was conceived as a follow-up of an earlier CRP on “Assessment of soil erosion through the use of ^{137}Cs and related techniques as a basis for soil conservation, sustainable production and environmental protection”. This earlier CRP has made a major contribution to coordinating efforts to refine and standardize the ^{137}Cs technique. These methodological developments are documented in the Handbook for the Assessment of Soil Erosion and Sedimentation using Environmental Radionuclides published by Kluwer Academic Publishers (Zapata, 2002). Further findings are reported in two special issues of the journals Acta Geologica Hispanica (Queralt et al., 2000) and Soil and Tillage Research (Zapata, 2003). They paved the way to both extending the approach to other environmental radionuclides, such as lead-210 (^{210}Pb) and beryllium-7 (^{7}Be), and expanding applications exploiting the essentially unique advantages provided by the technique. The basic principles involved in the application of these natural geogenic (^{210}Pb) and cosmogenic (^{7}Be) radionuclides in soil erosion and sedimentation studies are similar to those for the artificial radionuclide ^{137}Cs. When using several radionuclides, estimates of soil redistribution relating to different time scales (from less than one month with ^{7}Be (half-life of 53.4 days) up to fifty and one hundred years with ^{137}Cs (half-life of 30.2 years) and ^{210}Pb$_{ex}$ (half-life of 22.3 years), respectively) can be obtained using a single sampling campaign, thereby avoiding the time-consuming and costly installations and procedures commonly required by the non-nuclear methods to monitor study sites over extended periods of time (Mabit et al., 2008a).

To consolidate and refine these new advances and applications, a new CRP on “Assessing the effectiveness of soil conservation measures for sustainable watershed management and crop production using fallout radionuclides” (D1.50.08) was implemented between 2002 and 2008. The overall objective was to develop improved land use and management strategies for sustainable watershed management through effective soil erosion control practices. This CRP established a research network and supported the efforts of teams of scientists in sixteen Member States (Australia, Austria, Brazil, Canada, Chile, China, Japan, Morocco, Pakistan, Poland, Romania, Russia, Turkey, United Kingdom, United States of America and Vietnam) (Fig. 1).

The specific objectives of the CRP were:

(i) To further develop and refine fallout radionuclide methodologies, with particular emphasis on the use of ^{137}Cs, ^{210}Pb and ^{7}Be for measuring soil erosion over several spatial and time scales,
(ii) To establish standardized protocols for the application of the above techniques, and
(iii) To utilize these techniques to assess the impact of short- and medium-term changes in land use practices and the effectiveness of specific soil conservation measures.

The climatic, soil, topographical and land use conditions, under which the research teams applied FRN-based tools, varied considerably. One of the most significant consequences was the variability in FRN deposition histories and inventory levels. These initial fallout activities were in some cases quite low (Hai et al., 2004, 2006) or highly spatially variable (Golosov et al., 2008a; Belyaev et al., 2009). Nevertheless, the achievements of the CRP, as reflected by the results of the individual studies referred to in this overview, have demonstrated that FRN-based techniques are powerful tools to assess soil erosion/deposition at several spatial and temporal scales in a wide range of environments.

The established international research network confirmed that the ^{137}Cs technique is now recognized worldwide to be the primary and most widely used isotopic tracer for soil erosion/sedimentation investigations (Walling and He, 1999). The ^{7}Be technique, as reported by Blake et al. (1999) and Walling et al. (1999) has been further applied in this CRP to estimate short-term soil redistribution studies in a variety of environments. Particular applications included the assessment of the impacts of tillage systems and forest harvest operations (e.g. Schuller et al., 2006, 2007a; Sepúlveda et al., 2008; Fukuyama et al., 2010). New protocols were developed and tested for the application of ^{137}Cs, ^{210}Pb and ^{7}Be to obtain information on soil redistribution rates over short- and longer-term time scales and associated spatial patterns (Benmansour et al., 2006, 2010; Froehlich and Walling, 2005, 2007; Golosov et al., 2008b; Belyaev et al., 2009; Li et al., 2007b, 2011; Kato et al., 2010; Hai et al., 2004, 2006; Sepúlveda et al., 2008; Mabit et al., 2007; Wallbrink et al., 2005; Shakesby et al., 2006; Wilkinson et al., 2006; Zhang et al., 2003a,b, 2006a,b; Feng et al., 2004; Zheng et al., 2006, 2007; He et al., 2007). Repeated measurements were used to provide current, short-term assessments of soil redistribution and to improve the accuracy of ^{137}Cs results (Tiessen et al., 2009). Furthermore, this information has been used to assess the impact of different land use practices on soil redistribution rates (Benmansour et al., 2006, 2010, 2011; Nouira et al., 2007; Haciyakupoglu et al., 2005; Kiziltas et al., 2009; Mizugaki et al., 2008; Rhoton et al., 2008; Ritchie et al., 2009), their response to changes in land use (Froehlich and Walling, 2005, 2007; Wallbrink et al., 2005; Shakesby et al., 2006; Wilkinson et al., 2006; Li et al., 2009; Lobb et al., 2010; Schuller et al., 2004, 2007b; Sepúlveda et al., 2008), and the effectiveness of soil conservation measures (Bacchi et al., 2003; Pires et al., 2009; Belyaev et al., 2009; Golosov et al., 2008b; Li et al., 2011; Hai et al., 2004, 2006; Mabit et al., 2009; Nistor et al., 2007; Rafiq et al., in press; Schuller et al., 2004, 2006, 2007a,b; Sepúlveda et al., 2008; He et al., 2007) in inducing or controlling soil erosion. In the framework of the CRP a standardized

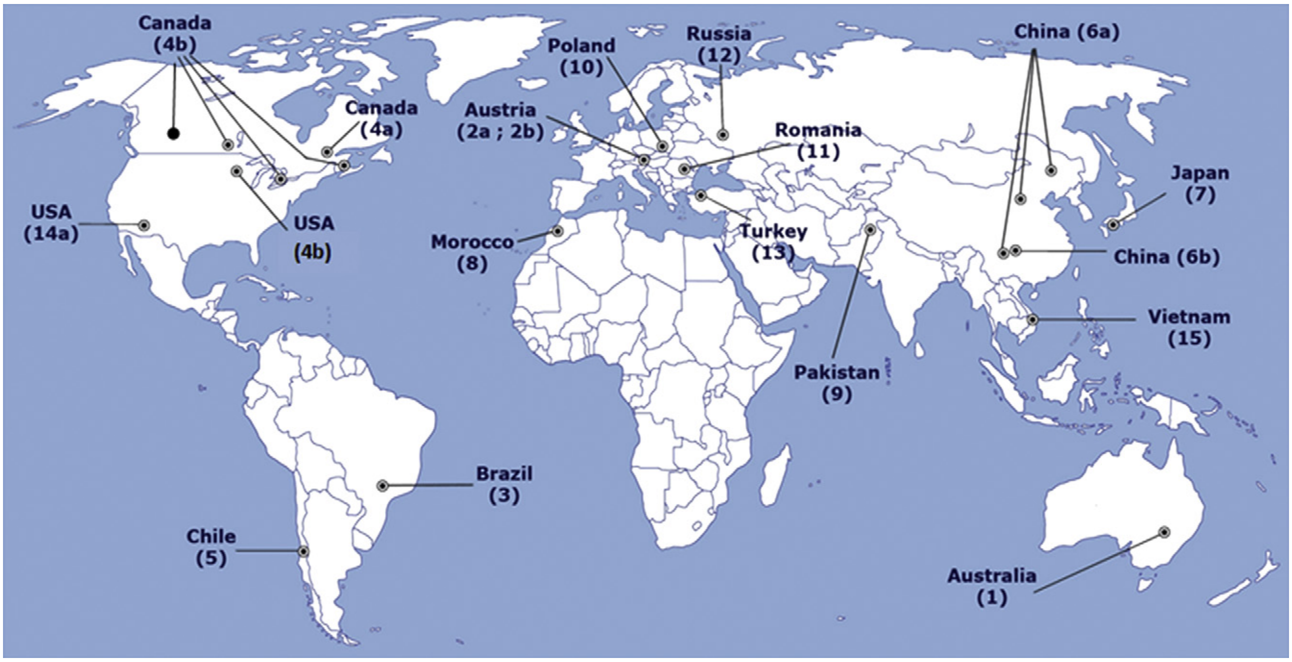

Fig. 1. Location of the study areas investigated by the 19 different Coordinated Research Project participants. (1) Wilkinson et al., 2006, (2a) Mabit et al., 2009, (2b) Wollelo and Klik, 2010, (3) Bacchi et al., 2003, (4a) Mabit et al., 2007, (4b) Lobb et al., 2010, (5) Schuller et al., 2007a,b, (6a) Li et al., 2006, 2007b, (6b) Zhang et al., 2006a,b, (7) Onda et al., 2011, (8) Benmansour et al., 2010, 2011, (9) Rafiq et al., in press, (10) Froehlich and Walling, 2005, (11) Popa et al., 2006, 2007, (12) Golosov et al., 2008a,b, (13) Haciyakupoglu et al., 2005, (14) Ritchie et al., 2009, (15) Hai et al., 2006.

set of conversion models was developed for use with ^{137}Cs, ^{210}Pb$_{ex}$ and ^{7}Be measurements to estimate soil redistribution rates (Walling et al., 2008). The different models provide a simple means of deriving estimates of soil redistribution rates from FRN measurements. Furthermore, the reliability of the estimates of soil redistribution rates obtained using the conversion models was demonstrated by comparisons with information provided by conventional, often more costly and time-consuming, non-isotopic techniques, such as erosion pins, erosion modeling (e.g. USLE, RUSLE, WEPP), sediment yields and reservoir silting measurements, runoff plot monitoring data and sediment traps (e.g. Bacchi et al., 2003; Correchel et al., 2005; Froehlich and Walling, 2005, 2007; Mabit et al., 2007, 2009; Popa et al., 2006, 2007; Schuller et al., 2006). Linkage between ^{137}Cs and parameters like soil organic carbon and soil texture has been confirmed or established (Wollelo and Klik, 2010; Li et al., 2006, 2007a,b, 2008b; Mabit et al., 2008b; Mabit and Bernard, 2010). Finally the IAEA also supported the CRP through the coordination of a proficiency test for ^{137}Cs and total ^{210}Pb measurements (Shakhashiro and Mabit, 2009).

Specific research results and recommendations arising from this CRP are summarized in this review paper according to the three major objectives of the project. More detailed information can be found in the project report (IAEA, 2011).

2. Development and refinement of fallout radionuclide methodologies

The key focus of the CRP was to develop novel applications of FRN for assessing the impact of soil conservation measures on soil erosion and sedimentation with an emphasis on the combined use of ^{137}Cs, ^{210}Pb$_{ex}$ and ^{7}Be for measuring soil erosion over several spatial and temporal scales.

Schuller et al. (2004) exemplified the potential of detailed measurements of ^{137}Cs depth distributions and inventories to establish changes in soil redistribution rates over the period following global bomb fallout, in response to a major change in the tillage system. The Chilean research team developed methods for using measurements of the ^{137}Cs depth distribution and inventory to estimate soil redistribution rates at sampling points under the original conventional tillage and after the shift to a no-till system. This approach should be applicable wherever a change from conventional tillage to no-till has occurred. However, the approaches are constrained by the requirement for relatively long periods (10–15 years) under the contrasting tillage systems.

In Russia, Belyaev et al. (2009) tested the approach of the combined use of Chernobyl and bomb ^{137}Cs to investigate changes in soil redistribution rates associated with the post-Chernobyl period. The utilization of this approach was limited to those areas of Europe where bomb and Chernobyl fallout inventories were of similar magnitude. However, in the case study described by Belyaev et al. (2009) the technique appeared to overestimate the actual erosion rates, due to the influence of extreme erosion during the period immediately after the Chernobyl accident and prior to incorporation of the fresh Chernobyl fallout into the plough layer by tillage. This study indicates there is a need for further research on the possible influence of extreme erosion events prior to homogenization of the vertical ^{137}Cs distribution in the plough layer by tillage mixing.

This CRP demonstrated the potential for using ^{7}Be to provide information on short-term rates of soil redistribution. The successful use of ^{7}Be measurements to quantify erosion rates during individual events or short periods of heavy rainfall has been reported by the scientific teams from Morocco, Vietnam, Chile, Australia, and China (Benmansour et al., 2006, in press; Nouira et al., 2007; Hai et al., 2004, 2006; Schuller et al., 2006, 2007a; Sepúlveda et al., 2008; Wallbrink et al., 2005; Shakesby et al., 2006; Wilkinson et al., 2006; Li et al., 2011). The approach clearly involves a number of complexities, as it requires careful selection of the study period and detailed soil sampling. To determine the effectiveness of soil conservation measures, it is necessary to have control areas for comparison purposes. The information on event-related erosion generated by the ^{7}Be measurements can provide a useful complement to the use of ^{137}Cs measurements to document the mean annual erosion rates associated with specific land use systems and different soil conservation practices.

The potential for using ^{210}Pb measurements to estimate soil redistribution rates was also explored. However, only 31% of the participants were able to provide acceptable results for total ^{210}Pb analyses (Shakhashiro and Mabit, 2009). Once this analytical capacity is improved it seems that the use ^{210}Pb measurements as a complement to ^{137}Cs offers considerable potential (Benmansour et al., 2006, 2010, in press; Froehlich and Walling, 2005, 2007; Belyaev et al., 2009; Li et al., 2011; Fukuyama et al., 2008; Wallbrink et al., 2005; Shakesby et al., 2006; Wilkinson et al., 2006; Zhang et al., 2006a,b; Zheng et al., 2007; He et al., 2007). However, in Russia Belyaev et al. (2009) found that ^{210}Pb$_{ex}$ fallout was characterized by substantially higher local variability than that of ^{137}Cs, posing an important potential limitation in the use of ^{210}Pb$_{ex}$ for documenting soil redistribution. This constraint was also highlighted by Mabit et al. (2009) in an investigation in North-East Austria. While ^{137}Cs produced meaningful and viable results, the ^{210}Pb method was not applicable due to very low concentrations of ^{210}Pb$_{ex}$ which resulted also in a high uncertainty for the measurements.

However, Belyaev et al. (2009) found that the variation of the relative inventories of ^{137}Cs and ^{210}Pb$_{ex}$ along their studied transects followed a similar pattern for most parts of the transects. The results from the CRP generally support the conclusion that ^{210}Pb$_{ex}$ can potentially be employed for quantification of soil redistribution, but more research is needed to evaluate the various factors influencing the spatial variability of ^{210}Pb fallout. Because of this variability, there is a need to consider carefully both the number of reference sites to be sampled when using ^{210}Pb$_{ex}$ and the number of sampling points at individual reference sites.

The CRP focused also on the combined use of ^{137}Cs, ^{210}Pb$_{ex}$ and ^{7}Be. The studies reported by Benmansour et al. (2011), Froehlich and Walling (2005, 2007), Belyaev et al. (2009), Gennadiyev et al. (2006), Li et al. (2011), Onda et al. (2011), Hai et al. (2004, 2006), Sepúlveda et al. (2008), Wallbrink et al. (2005), Shakesby et al. (2006), Wilkinson et al. (2006), Zhang et al. (2004), Zheng et al. (2007) and He et al. (2007) demonstrated the potential for using two or three of these radionuclides in combination to derive information on changes in soil redistribution rates through time, sediment source identification and on the efficiency of soil conservation measures. Examples of these applications are provided below in Section 3. Research conducted by Tiessen et al. (2009) indicated that repeated measures of ^{137}Cs can provide accurate assessments of soil erosion over time scales of 5–15 years. The greatest accuracy is achieved in areas of the landscape subject to severe soil loss, that is, to upper slopes. Since these areas are where farmers most often observe crop loss and inefficiencies in cropping inputs, they are the areas that drive changes in land management, the adoption of conservation tillage, soil–landscape restoration and/or precision farming techniques. Additionally, Froehlich and Walling (2005, 2007), Onda et al. (2007), Mizugaki et al. (2008), Rhoton et al. (2008), Ritchie et al. (2009), Wilkinson et al. (2006) and Zhang et al. (2004) demonstrated the potential for using fingerprinting techniques for discriminating and identifying suspended sediment sources (e.g. sheet erosion, rill and gully erosion and channel erosion). Coupled with an appropriate experimental design this approach can afford a powerful tool for assessing changes in sediment sources resulting from the introduction of soil conservation measures. In a study of the lake Burragorang catchment in Australia following a severe wildfire, Wilkinson et al. (2006) compared the ^{137}Cs and ^{210}Pb$_{ex}$ concentrations associated with eroded surface soil and river sediment and showed that a high proportion of the post-fire river sediment comprised surface material. Similarly, Rhoton et al. (2008) and Ritchie et al. (2009) used ^{137}Cs measurements to establish which sub-areas within a semi-arid rangeland watershed in Arizona, USA were contributing to the suspended sediment load in the stream. These measurements indicated that most of the suspended sediment sampled at the outlet of the watershed was derived from shrub dominated sub-watersheds. Based on these results, it was suggested that management of these semi-arid rangelands must consider techniques that will protect grass dominated areas from shrub invasion. Froehlich and Walling (2005, 2007) working in the Polish Flysh Carpathian Mountains also showed how changes in the ^{210}Pb$_{ex}$, ^{7}Be and ^{137}Cs content of suspended sediment transported by a river during flood events reflected changes in the relative contribution of different sediment sources. During extreme storm events, the contributing area was greatly expanded and sediment was mobilized from areas which are unconnected to the stream during ‘normal’ events. Unpaved roads were identified as the main source of the suspended sediment load. Mizugaki et al. (2008) were also able to identify the forest floor as the most important source of fluvial sediment in mountainous forested catchments in southern Japan, by comparing the radionuclide content of suspended sediment with that of potential source materials. Using the same approach Zhang et al. (2004) were able to rank different sediment sources in terms of the relative magnitude of their sediment contribution in his study area in NE China.

The FRN can also be used to provide an improved understanding of organic carbon losses from fields and watersheds. Li et al. (2006, 2007b, 2008b), Mabit and Bernard (2010) and Mabit et al. (2008b) showed how estimates of soil redistribution rates obtained from ^{137}Cs and/or ^{210}Pb$_{ex}$ measurements could be used to better understand how soil organic carbon content is influenced by tillage and water erosion, and how the related soil health (Wollelo and Klik, 2010) can be improved by specific soil conservation measures.

3. Establishment of standardized protocols for the combined application of the above techniques

Although basic procedures, in particular for ^{137}Cs-based techniques, are now well established, the different case studies developed in this CRP identified a number of technical challenges in applying and developing the approaches outlined above. These challenges, which are described below, emphasize that there is not one single method that can be used universally when applying FRN-based techniques in estimating soil redistribution or assessing the efficiency of soil conservation measures.

Methods need to be specific to the FRN being used, the research questions being asked, the environmental conditions under which the study is being carried out and the local land management conditions. However, the CRP teams addressed most of the main challenges involved in the use of FRN to develop improved land use and management strategies for sustainable watershed management through effective soil erosion control practices.

The environmental conditions, under which FRN are currently being applied, vary considerably. As mentioned above, one of the most important consequences was the wide range of current inventory levels and associated FRN deposition histories. In some circumstances, low FRN activities (e.g. ^{137}Cs inventories in the southern hemisphere, ^{210}Pb$_{ex}$ in coastal zones with prevailing onshore winds or high levels of supported ^{210}Pb relative to excess ^{210}Pb) can be dealt with by counting samples for a longer duration (requiring more detectors, longer studies, or alternate sampling strategies – bulking) or by using more efficient detectors (requiring further capital investment). Nevertheless, practical limits may exist.

The importance of employing geostatistical tools in studies using FRN to estimate soil redistribution rates and sediment budgets has also been demonstrated (Mabit and Bernard, 2007; Mabit et al., 2008b). The use of such spatial analysis approaches can provide a valuable contribution to developing a better understanding of the impact of land and water management practices on soil redistribution, so that the best and most-effective conservation practices can be identified to maximize the efficiency of soil and water conservation.

Reliable reference sites can be difficult to establish due to the high degree of variability in local precipitation (Belyaev et al., 2009) and the difficulty of identifying undisturbed sites (Haciyakupoglu et al., 2005). In particular finding suitable reference sites in mountainous regions and areas under intensive cultivation can be a challenge (Mabit et al., 2009). In addition, when the study area is large, it is important to select several reference sites. In this respect, it is essential that care should be taken when establishing the FRN reference inventory in a study area.

Measurements themselves cannot provide the information or answers required. They must be used as a tool within an appropriate and sound experimental design. This CRP has demonstrated that when applied appropriately FRN can provide a valuable tool for addressing a wide range of questions related to the impact of land use practices in inducing or controlling soil erosion (Benmansour et al., 2011; Haciyakupoglu et al., 2005; Kiziltas et al., 2009; Fukuyama et al., 2010; Rhoton et al., 2008; Ritchie et al., 2009), land use change (Froehlich and Walling, 2005, 2007; Wallbrink et al., 2005; Shakesby et al., 2006; Wilkinson et al., 2006; Li et al., 2009; Lobb et al., 2010), and the effectiveness of soil conservation measures (Bacchi et al., 2003; Golosov et al., 2008b; Belyaev et al., 2009; Li et al., 2011; Hai et al., 2004, 2006; Mabit et al., 2009; Nistor et al., 2007; Rafiq et al., in press; Schuller et al., 2007b; Sepúlveda et al., 2008; He et al., 2007).

Measurement of radionuclides by HPGe gamma spectrometry forms an essential component of the application of FRN techniques in soil erosion and sedimentation studies. From the performance evaluation undertaken for a proficiency test carried out during the CRP it was found that 66% of the 14 laboratories involved reported “acceptable” results for ^{137}Cs measurements, whereas only 31% of the participants were able to provide acceptable results for total ^{210}Pb analyses (Shakhashiro and Mabit, 2009). Difficulties were also apparent in the measurement of low levels of ^{137}Cs activity (2.6 ± 0.2 Bq kg^{-1}), with more than 40% of results scored as unacceptable.

The results from the proficiency test underlined the necessity for the IAEA to regularly organize intercomparison exercises for FRN analyses for laboratories participating in CRPs and Technical Cooperation Projects (TCPs).

In this CRP a generally applicable set of conversion models was developed by researchers at the University of Exeter for use with ^{137}Cs, ^{210}Pb$_{ex}$ and ^{7}Be measurements to estimate soil redistribution rates (Walling et al., 2008). The models included six models for use with ^{137}Cs measurements, three models for use with ^{210}Pb$_{ex}$ measurements and a single model for use with ^{7}Be measurements. The ^{137}Cs and ^{210}Pb$_{ex}$ models include models applicable to cultivated and uncultivated land. The model developed for ^{7}Be is applicable to both cultivated and uncultivated land. Furthermore, in order to facilitate the application of the models in a standardized manner, and to promote their use by the wider scientific community, a user-friendly software package, based on an Excel Add-in has been produced and made available to interested persons. The model software also contains several routines for estimating key parameters. In addition a refined ^{7}Be conversion model which extended the timescale over which ^{7}Be measurements can be used from a few weeks to several months was also developed (Walling et al., 2009).

The models are available on the following website: http://www-naweb.iaea.org/nafa/swmn/swmcn-databases.html. It is hoped that the use of a standardized set of conversion models by researchers will facilitate exchange and comparison of results and that the wider testing of the conversion models will generate an improved understanding of their advantages and limitations and thus assist the further development and improvement of such models.

4. Use of FRN techniques to assess the impact of short- and medium-term changes in land use practices and the effectiveness of specific soil conservation measures

The FRN techniques have been used to assess the impact of land use and agricultural management practices in inducing or controlling soil erosion. These studies have investigated the impacts of different land management practices (Benmansour et al., 2006, 2011; Nouira et al., 2007; Kiziltas et al., 2009; Haciyakupoglu et al., 2005; Ertek et al., 2004; Fukuyama et al., 2010; Rhoton et al., 2008; Ritchie et al., 2009), land use change (Froehlich and Walling, 2005, 2007; Wallbrink et al., 2005; Shakesby et al., 2006; Wilkinson et al., 2006), and the effectiveness of soil conservation measures such as riparian strips, zero-tillage, conservation agriculture, grass barriers, contour cropping, and others (Pires et al., 2009; Golosov et al., 2008b; Belyaev et al., 2009; Li et al., 2011; Hai et al., 2004, 2006; Mabit et al., 2009; Nistor et al., 2007; Rafiq et al., in press; Schuller et al., 2007b; Sepúlveda et al., 2008; He et al., 2007). Several examples are provided below.

Schuller et al. (2007b) reported that implementing conservation agriculture (with zero-tillage and the retention of crop residues) in southern Chile, about 16 years ago reduced the mean annual net erosion rates in a cereal field, as documented using ^{137}Cs measurements, by about 87% (from 11 t ha^{-1} year^{-1} to 1.4 t ha^{-1} year^{-1}) with the proportion of the study area subject to erosion reducing from 100% to 57%. However, the beneficial effects of such management change can be readily lost if the mulch layer of old crop residues is removed by burning. The same research team used the short-lived radionuclide ^{7}Be to document the erosion resulting from a short period of intense rainfall occurring after the dramatic burning of the crop residues (Sepúlveda et al., 2008). The results provided evidence of substantial net erosion of 12 t ha^{-1} over this 27-day period (400 mm rainfall). This represented a dramatic increase over the average annual soil loss under conservation agriculture of 1.4 t ha^{-1}. Li et al. (2011) similarly used ^{7}Be measurements in their studies in NE China to show that zero-tillage in combination with the retention of crop residues could reduce soil erosion by 33%, as compared with conventional tillage practices. Similar results were reported in Morocco (Benmansour et al., 2006, 2011; Nouira et al., 2007).

Wallbrink et al. (2005), Shakesby et al. (2006) and Wilkinson et al. (2006) showed in their Australian case study that significant amounts of sediment and attached nutrients were eroded from burnt hillslopes in the months following a fire event. Comparison of the concentrations of ^{137}Cs and ^{210}Pb$_{ex}$ associated with eroded surface soil and river sediment showed that the latter was derived primarily from surface erosion of the hillslopes after the fire, in contrast to the pre-fire situation, where the sediment was dominated by sub-surface material mobilized from river channels and gullies.

Using the ^{137}Cs technique, Pires et al. (2009) highlighted that the minimum width of 30 m for riparian zones, prescribed by Brazilian Environmental Law, is not always sufficient to ensure that the riparian vegetation functions effectively as a sediment trap. Bacchi et al. (2003) also used ^{137}Cs measurements to calibrate the process-based WEPP erosion model to better predict soil loss and sediment deposition in complex landscapes, such as riparian systems.

He et al. (2007) used ^{137}Cs and ^{210}Pb$_{ex}$ measurements on sloping cultivated land in the Sichuan basin in China to show that the traditional and centuries-old soil conservation measures can reduce soil losses by up to 35%, compared to losses on sloping land without conservation measures.

In Romania the extent of the area under soil conservation practices has declined by more than 60% since 1991, as a result of a change in government policy. The related law stipulated that the land had to be reassigned to the original landowners, resulting in the division of the agricultural land into long and narrow plots, which are often oriented downslope. The major impact of the law was the restoration of the traditional agricultural system, leading to increased soil erosion. Nistor et al. (2007) showed that erosion on the long and narrow plots without conservation was three times higher than in locations where soil conservation measures still existed.

5. Conclusions and prospect

The CRP has created an effective network of research scientists and national research institutes involved in the use of fallout radionuclides to *document soil redistribution rates and to* assess the relative impacts of different soil conservation measures on soil erosion and land productivity. The success of the CRP has stimulated an interest in many IAEA Member States in the use of these methodologies to identify factors and practices that can enhance sustainable agriculture and minimize land degradation. At present there are 37 Member States *where FRN are being used to address issues relating to sustainable land management* through TCPs at both national and regional levels. For example, a major regional project on *"Sustainable Land Use and Management Strategies for Controlling Soil Erosion and Improving Soil and Water Quality" (RCA Project RAS/5/043)* has recently been concluded. This project involved participants from the following 14 Member States in the East Asia and Pacific region: Australia, Bangladesh, China, India, Indonesia, Republic of Korea, Malaysia, Mongolia, Myanmar, Pakistan, Philippines, Sri Lanka, Thailand and Vietnam. FRN methodologies have been successfully used by the participating countries to assess soil erosion, to evaluate soil conservation measures (e.g. forestation, terracing, contour cropping, contour hedgerow systems), and to understand better the link between soil redistribution and soil quality (e.g. soil organic matter) in the landscape.

The success outlined above has stimulated additional commitment from the IAEA in responding to requests from Member States in Latin America. In 2009, a new regional TCP: RLA5051 on "*Using Environmental Radionuclides as Indicators of Land Degradation in Latin American, Caribbean and Antarctic Ecosystems*" was initiated. This has been approved to run for 5-years duration from 2009 until 2013. The following 14 Member States are participating: Argentina, Bolivia, Brazil, Chile, Cuba, Dominican Republic, El Salvador, Jamaica, Haiti, Mexico, Nicaragua, Peru, Uruguay and Venezuela. The project aims to enhance soil conservation and environmental protection in Latin American, Caribbean and Antarctic environments, in order to ensure sustainable agricultural production and reduce the on- and off-site impacts of land degradation.

The network also acknowledged the potential for further development of FRN applications, in particular the upscaling this area of research to the catchment level and linking it with sediment source fingerprinting techniques to improve environmental quality in developing Member States. The network recommended that the IAEA should support these investigations through the Coordinated Research Programme. In this context, action was taken by organizing a Consultants Meeting on Integrated approaches for the assessment of land use impacts on soil loss and related environmental problems in Vienna, from November 5–7 November, 2007. A new CRP proposal (D1.20.11: "*Integrated Isotopic Approaches for an Area-wide Precision Conservation to Control the Impacts of Agricultural Practices on Land Degradation and Soil Erosion*") emphasizing the identification of critical areas of soil loss was formulated and approved and the project started in June 2009. This CRP focuses on the catchment scale integration of fingerprinting techniques, such as Compound Specific Isotope Analysis (CSIA), with the use of FRN.

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The passing of our colleague and CRP participant Dr. Jerry Richie in June 2009 came as a big shock to the community. Jerry was one of the pioneers in the use of FRN and a key member of our FRN coordinated research networks. His friendship and support to all team members within the various previous CRPs in which he was involved was greatly valued and will be long remembered.

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