Promoting the use of isotopic techniques to combat soil erosion: An overview of the key role played by the SWMCN Subprogramme of the Joint FAO/IAEA Division over the last 20 years

Lionel Mabit1 | Claude Bernard2 | Amelia Lee Zhi Yi1 | Emil Fulajtar1 | Gerd Dercon1 | Mohammad Zaman1 | Arsenio Toloza1 | Lee Heng1

1 Soil and Water Management & Crop Nutrition Subprogramme, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, International Atomic Energy Agency, 1400 Vienna, Austria
2 Institut de recherche et de développement en agroenvironnement, Québec (Québec) Canada, G1P 3W8

Correspondence
L. Mabit, Soil and Water Management & Crop Nutrition Subprogramme, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, International Atomic Energy Agency, 1400 Vienna, Austria.
Email: l.mabit@iaea.org

Abstract
The International Atomic Energy Agency (IAEA), through the Joint Division with the Food and Agriculture Organization (FAO) of the United Nations, assists its Member States in applying nuclear techniques to alleviate challenges in food safety, food security and sustainable agricultural development. The Soil and Water Management & Crop Nutrition (SWMCN) Subprogramme, within the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, has made significant contributions to the development of isotopic techniques for the assessment of soil degradation and the development of efficient soil and land conservation approaches. These techniques include fallout radionuclides such as $^{137}$Cs, $^{210}$Pbex, $^{7}$Be, and $^{239+240}$Pu as well as $^{13}$C stable isotope and compound-specific stable isotope analyses. These methodologies were developed and/or refined through the work of researchers from developed and developing countries who were selected to work within the frame of IAEA’s Coordinated Research Projects (CRPs). Internal research activities implemented in the Joint FAO/IAEA’s SWMCN Laboratory in Seibersdorf supported the work accomplished in the CRPs. The methodologies thus developed have been subsequently disseminated to developing countries by IAEA’s Technical Cooperation Programme to assist Member States to adopt climate-smart agriculture and reduce soil degradation that poses a threat to food security and the environment. This review paper provides an overview of the activities conducted in the frame of CRPs for combating soil erosion over the last 20 years and highlights the major achievements. Examples of the success and the impact obtained in Morocco, Madagascar, and Vietnam in using these isotopic techniques are presented.

KEYWORDS
climate change, fallout radionuclides, soil degradation, soil tracers, stable isotopes
1 INTRODUCTION

A major challenge for the global population is to ensure food security. It is projected that the world population will exceed 9 billion by the year 2050, and therefore food production would have to be doubled to fulfill this requirement. This need will occur principally in developing countries, where most people rely on agriculture for their livelihood (Food and Agriculture Organization [FAO], 2015, 2017; United Nations Environment Programme, 2015).

Model projections suggest that global surface temperature at the end of the 21st century is likely to exceed 1.5 °C relative to the period 1850–1900 (Intergovernmental Panel on Climate Change [IPCC], 2013). The latest 2014 report produced by the IPCC stresses the projected impact of climate change, highlighting hazards, vulnerability, and exposure resulting from these changes (IPCC, 2014). To address these critical issues of climate change and population growth, the FAO and the global scientific community are helping farmers to develop climate-smart agricultural practices and systems, which can adapt to the impacts of climate change and variability (i.e., climate change adaptation). Although having the potential to increase food production, these practices also improve soil and water management and reduce land degradation, and associated soil carbon loss and greenhouse gas emissions (i.e., climate change mitigation; FAO, 2013).

Land degradation and soil erosion by water are associated with the irreversible loss of fertile soil, reduced soil productivity, increased siltation and pollution of water bodies.

The annual global cost of soil erosion and its associated downstream sedimentation were established to be approximately U.S. $400 billion (Pimentel, 2006). Land degradation also increases CO₂-induced climate change through release of CO₂ (WMO, 2005). In particular, by significantly reducing soil quality and fertility, soil erosion may contribute to intensifying the impact of climate change. Erosion leads to soil disruption and aggregate breakdown and, hence, partial mineralization of soil organic carbon and CO₂ release (Lal, 2004; Lal, Griffin, Apt, Lave, & Morgan, 2004; Lal & Pimentel, 2008; Ran, Lu, & Xin, 2014; Reichstein et al., 2013).

Current social and economic impacts related to soil degradation have generated a pressing need for obtaining accurate information on soil erosion magnitudes affecting agricultural land to strengthen soil conservation strategies.

The quest for new techniques for evaluating long- to short-term soil loss and deposition processes to complement modelling and conventional measurement methods, which require a large number of parameters and many years of measurements, has led to the development and refinement of alternative approaches such as the use of fallout radionuclides (FRNs). Four major FRNs are used as soil erosion tracers (Table 1 and Figure 1) including anthropogenic radionuclides such as the medium-lived caesium-137 (137Cs) and the long-lived isotopes of plutonium (239+240Pu), originating from atmospheric nuclear weapon tests and from nuclear power plant accidents, and natural radionuclides such as the medium-lived geogenic lead-210 (210Pbex) and short-lived cosmogenic beryllium-7 (7Be) (see Alevew, Pitois, Meusburger, Ketterer, & Mabit, 2017, Alevew, Meusburger, Juretzko, Mabit, & Ketterer, 2014; Guzmán, Quinton, Nearing, Mabit, & Gómez, 2013; International Atomic Energy Agency [IAEA], 2014; Mabit, Benmansour, & Walling, 2008; Mabit, Meusburger, Fulajtar, & Alewell, 2013; Mabit et al., 2014; Matisoff, 2014; Matisoff & Whiting, 2011; Taylor, Blake, Smith, Mabit, & Keith-Roach, 2013; Zapata, 2002).

The main assumption for the use of these radiotracers in soil erosion and sedimentation investigations is similar. When deposited on the soil surface, they are strongly bound to soil colloid particles (clay and organic matter) and move in the environment by mechanical processes such as soil erosion (water, wind, or tillage erosion). To use FRN methods, it is necessary to establish the content of FRNs at a reference location (i.e., an undisturbed site where neither significant erosion nor deposition is occurring) located near the study area. Investigated areas are identified as erosional or depositional by comparing their FRN inventories with those of the reference site. Levels below the reference site value will indicate soil eroded, and those in excess indicate soil deposited (see IAEA, 2014; Mabit, Benmansour, & Walling, 2008; Zapata & Nguyen, 2009). A recent animated infographic presenting the 137Cs method has been made available online by the Joint FAO/IAEA Division to provide an easily understandable illustration of the principles underlying the technique and the potential use of 137Cs for quantifying soil erosion/deposition processes (see https://youtu.be/hgfaYLvzs_U?list=PLzp5NgJ2-dK7maiX4U8aqEio1wXmeQrv).

To ensure sustainable agricultural management, there is a need not only to quantify soil erosion rates but also to localize the sources of land degradation in the landscape, to identify appropriate conservation measures, and to test and assess their efficiency.

### TABLE 1 Summary of the main FRNs used as soil tracers to investigate the magnitude of soil redistribution (adapted from Mabit, Benmansour, & Walling, 2008)

| FRN | Origin     | Periodic table element group | Half-life                  | Required analytical facility | Scale of application          |
|-----|------------|------------------------------|----------------------------|------------------------------|-------------------------------|
| 137Cs | Anthropogenic | Alkali metal | 30.2 years | GS | Plot to large watershed |
| 239+240Pu | Anthropogenic | Actinide | 24,110 years (239Pu) and 6,561 years (240Pu) | ICP-MS, AS, AMS | Field |
| 210Pb | Natural geogenic | Posttransition metal | 22.8 years | GS, LSC, AS | Plot to watershed |
| 7Be | Natural cosmogenic | Alkaline earth metal | 53.3 days | GS | Plot to field |

Notes. FRN = fallout radionuclide; GS = gamma spectroscopy; LSC = liquid scintillation counting; ICP-MS = inductively coupled plasma mass spectrometry; AS = alpha spectrometry; AMS = accelerator mass spectrometry.

aGS requiring a broad energy range high-purity germanium gamma detector.
bAS indirect measurement through 210Po.
Information on sediment sources can be obtained by studies involving the abundance of the $^{13}$C stable isotope and its different $\delta^{13}$C signatures in C$_3$ and/or C$_4$ plants (e.g., Laceby, Olley, Pietsch, Sheldon, & Bunn, 2015; Schindler Wildhaber, Liechti, & Alewell, 2012). Additional information can be gained using compound-specific stable isotope (CSSI) techniques. This technique is based on the fact that plants label the soil by organic biomarkers, which are absorbed by mineral particles of soils and are further redistributed in the environment through soil movement, in a way somewhat similar to FRNs. Depending on the plant species, these biomarkers have a different stable isotopic signature, making them suitable for discriminating and apportioning the sources of soil contribution that originate from different land uses (Gibbs, 2008; Reiffarth, Petticrew, Owens, & Lobb, 2016; Upadhayay et al., 2017; see Figure 1). For agri-environmental investigations, CSSI techniques are based on the soil determination of $^{13}$C natural abundance signatures of biomarkers such as the fatty acids (FAs).

This paper reviews 20 years of technical and scientific achievements in the use of isotopic and nuclear techniques to combat soil erosion and support soil conservation, as supported by the Soil and Water Management & Crop Nutrition (SWMCN) Subprogramme of the Joint FAO/IAEA Division through its research programme.

2 | THE USE OF FRNs AS SOIL REDISTRIBUTION INDICATORS

The quantitative assessment of soil erosion is not an easy task, and various methods have been introduced (erosion plots, erosion pins, volumetric measurements of rills, suspended sediment measurements in water courses, wind erosion traps, etc.). All these approaches have their advantages and their conceptual and technical limitations. The use of FRNs as soil redistribution indicators started in the late 1960s and reached a more routine status in the 1990s. The spatial redistribution of FRNs in the landscape reveals the combined magnitude of all soil movements (gross and net erosion, deposition) for time spans ranging from a few rain events ($^7$Be) to circa 60 years ($^{137}$Cs and $^{239+240}$Pu) and up to some 100 years for $^{210}$Pb$_{ex}$ (Mabit, Benmansour, & Walling, 2008). When compared with those of conventional measurement, soil redistribution rates derived from FRNs require only one field campaign, making this approach time and resource efficient.

Like all other techniques or approaches, FRN-based methods have their strengths and limitations. Besides, they are based on some key assumptions (i.e., uniform initial spatial distribution, and fast and almost irreversible adsorption to fine soil particles) that need to be met to ensure the reliability of the results generated.

FIGURE 1  Compound-specific stable isotope and fallout radionuclides: Two complementary techniques to investigate soil erosion, transport, and sedimentation processes [Colour figure can be viewed at wileyonlinelibrary.com]
Using FRNs requires that at each sampling point, the total isotope inventory is measured, to ensure appropriate comparison of the study site with the reference site. The selection of appropriate reference sites unaffected by erosion processes is also crucial. An in-depth understanding of particle sorting during erosion and deposition phases is important when interpreting FRN redistribution data, as FRNs are fixed preferentially to fine particles. Otherwise, soil loss rates could be overestimated and deposition rates underestimated. The analysis of FRNs in soils and sediments requires specialized equipment (e.g., gamma spectrometry for $^{137}$Cs and $^7$Be, gamma spectrometry and/or and alpha spectrometry for the determination of $^{210}$Pb$_{ex}$) as well as trained staff.

By essence, all assessment methods—even the more mature ones—have shortcomings that can be improved upon. For example, the pros and cons of the $^{137}$Cs method have been discussed and debated within the scientific community (Mabit et al., 2013; Parsons & Foster, 2011), and, as constructive follow-up, pragmatic proposals to refine this method have been suggested (e.g., Zhang, Zhang, & Wei, 2015). As mentioned by Mabit et al. (2013) and confirmed by Zhang et al. (2015), a sound sampling design is crucial when using this method to obtain reliable soil erosion rate estimates. In addition to scaling issues, comparison with direct measurements and monitoring methods should always be performed considering the processes involved by the different methods and the time scales investigated. Moreover, the major advantages and disadvantages of FRNs were already discussed in detail both in several review papers focusing on $^{137}$Cs (Mabit, Benmansour, & Walling, 2008; Walling & Quine, 1991), $^7$Be (Taylor et al., 2013), $^{210}$Pb$_{ex}$ (Mabit et al., 2014), and $^{239+240}$Pu (Alewell et al., 2017) and in a comprehensive handbook summarizing the experience of last decades of scientific activities conducted by using these radioactive tracers (IAEA, 2014).

For this reason, the detailed methodological assumptions and limitations of FRN methods will not be presented here, as the objective of this paper is to provide an overview of the involvement of IAEA in the development of FRN methods over the last decades.

3 | THE JOINT FAO/IAEA DIVISION OF NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

Established in 1964, the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture promotes the safe, secure, and peaceful use of nuclear technologies in food and agriculture. Since the end of the 1990s, the Joint FAO/IAEA Division contributed to improving land management and increasing the effectiveness of soil conservation measures. More information on the various activities conducted by the SWMCN Subprogramme can be found in Zapata et al. (2015).

Through international cooperation in research, training, and several outreach activities, including technical support to the IAEA’s Department of Technical Cooperation, these techniques that contribute to improving land management and soil conservation have been disseminated worldwide. To date, more than 70 FAO Member Countries and IAEA Member States have directly or indirectly benefited from the technical support and guidance of the Joint FAO/IAEA Division in using FRNs and stable isotopic methods to trace soil redistribution and evaluate soil loss at various spatial and temporal scales, and to quantify concretely soil conservation effectiveness for ensuring sustainable local and regional land management (see Figure 2).

The IAEA’s Coordinated Research Programme brings together scientists from FAO Member Countries and IAEA Member States to collaborate on common research issues. Each Coordinated Research Project (CRP) gathers a network of 5 to 15 national research institutions, working on a common global or regional scientific concern that can be tackled using isotopic technologies.

CRP participants have three potential different statutes. The research agreement holders—generally from developed countries—are expected to provide expertise at the highest scientific level and to contribute to the development and the refinement of the methodology. They are selected among most advanced scientists at the field of interest who are known to perform ‘cutting-edge science.’ The technical contract holders are recruited and funded to accomplish

FIGURE 2  Countries that have benefited from the support of the SWMCN Subprogramme in using fallout radionuclides and/or compound-specific stable isotope techniques [Colour figure can be viewed at wileyonlinelibrary.com]
various specific scientific or technical tasks in support of the CRP participants and to provide up-to-date expertise. The research contract holders—generally from developing countries—benefit from funding that covers expendable supplies, minor equipment items, field experiments, and so on. They are encouraged to develop case studies and are selected among well-established scientists able to implement new methodological tests. All these participants benefit from logistical and networking support and are entitled to attend a meeting, every 18 months or so, organized by and at the Agency’s expense.

CRPs represent unique international research networks, which have a huge potential for the development of methodologies due to well-balanced geographical coverage of various agro-environmental conditions. The findings of these research activities are disseminated to all Member States through national and international peer-reviewed publications as well as through IAEA scientific and technical publications, and other communication media. CRPs also support the implementation of the Agency’s Technical Cooperation Projects through the transfer of knowledge gained (IAEA, 2017).

More detailed and complementary information can be found at the Coordinated Research Activities website http://cra.iaea.org.

4 | CONFIRMING AND IMPROVING THE FRN METHOD

The use of nuclear techniques (especially the $^{137}$Cs method) for erosion and sedimentation assessments started in the 1960s and underwent, in the 1980s and 1990s, rapid methodological development that led to comprehensive agro-environmental evaluation tools. A major milestone was achieved at Exeter University (UK), with the development of conversion models for translating variations of $^{137}$Cs inventories into soil erosion/deposition rates (Walling & He, 1999; Walling & Quine, 1990).

In the mid-1990s, the IAEA became actively involved in the development of nuclear techniques through soil loss and sedimentation investigations (IAEA, 1995, 1998). From 1995 to 2001, the IAEA implemented two CRPs: (a) “Assessment of soil erosion through the use of $^{137}$Cs and related techniques as a basis for soil conservation, sustainable production, and environmental protection” (D1.50.05), led by the SWMCN Section, and (b) “Sedimentation assessment by environmental radionuclides and their application to soil conservation measures” (F3.10.01), led by the Isotope Hydrology Section.

The objectives of both CRPs were closely related, and their implementation was coordinated together through joint Research Coordination Meetings (Zapata, 2002). Several achievements originating from these CRPs are listed as follows: sampling strategies and improvements in establishing $^{137}$Cs reference values; upgrading the spatial scale of case studies from slope, plot, and field to watershed; introduction of the sediment budget concept and fingerprinting approaches; considering impacts of the Chernobyl accident for erosion studies in affected regions; testing of the $^{137}$Cs conversion models under different geographical conditions and in connection with various study purposes; and investigating other FRNs such as $^7$Be and $^{210}$Pb$_{ex}$ for erosion studies.

The FRN method thus began to be used routinely in a large number of situations worldwide and was focused on a wide range of research topics such as estimation of rates of particular erosion processes (such as gully erosion, tillage erosion, and wind erosion), assessment of land use impact, testing of conservation measures, and validation of erosion models and sediment chronology in reservoirs and on alluvial plains.

Through these two CRPs, the IAEA became actively involved in FRN methodology development. The results of the CRPs were disseminated through many scientific papers published by the participants and also in two special issues of international scientific journals (Queralt, Zapata, & Garcia-Agundo, 2000; Zapata, 2003). These papers involved a number of case studies dedicated to various topics such as the following:

- estimating the rates of particular soil erosion processes such as gully erosion (Ionita & Margineanu, 2000; Li, Poesen, Yang, Fu, & Zhang, 2003), wind erosion (Basher, 2000), and tillage erosion (Schuller, Ellies, Castillo, & Salazar, 2003);
- investigating the sediment stratigraphy in water reservoirs (Ionita, Margineanu, & Hurjui, 2000; Jones, Loughran, & Elliott, 2000) and on alluvial plains (Ionita & Margineanu, 2000);
- upgrading the $^{137}$Cs method application from plot to catchment scale (Bernard, Mabit, Wicherek, & Laverdière, 1998; Bujan et al., 2003; Mabit, Bernard, & Laverdière, 2002; Theocharopoulos et al., 2003; Wallbrink, Martin, & Wilson, 2003; Walling, He, & Whelan, 2003);
- implementing $^{137}$Cs method in areas affected by the Chernobyl accident (Fulajtar, 2000, 2003; Golosov, 2003; Ionita et al., 2000; Ionita & Margineanu, 2000);
- assessing the impact of land use changes and land management practices (Li, Lindstrom, Zhang, & Yang, 2000; Schuller et al., 2003; Wallbrink et al., 2003; Zhang, Quine, Walling, & Wen, 2000);
- assessing soil conservation efficiency of particular conservation measures such as grass hedges (Ritchie, 2000) and terracing (Zhang, Zhang, Wen, & Feng, 2003);
- using $^{137}$Cs for validation of erosion models such as agricultural nonpoint source pollution and areal nonpoint source watershed environmental response simulation (Walling et al., 2003);
- investigating the relation between $^{137}$Cs and specific land parameters such as slope inclination (Fulajtar, 2003; Pennock, 2003) and organic carbon (Mabit & Bernard, 1998; Ritchie & McCarty, 2003); and
- using $^{137}$Cs as soil quality indicator (Pennock, 2000).

However, the major achievement of the two CRPs was an overall standardization of the methodological approaches used by different research teams. Standardized methods and protocols were published in a widely accessible handbook edited by Zapata (2002). This handbook focuses on the $^{137}$Cs method but also provides information on $^{210}$Pb$_{ex}$ and $^7$Be. It also highlights methodological approaches that are needed for both erosion and sedimentation studies such as:

- guidelines on site selection and sampling design (Pennock & Appleby, 2002a);
sampling and sample pretreatment (Loughran, Wallbrink, Walling, & Appleby, 2002; Pennock & Appleby, 2002b);

• gamma spectrometry for FRN measurements (Wallbrink, Walling, & He, 2002);

• assessment of spatial distribution of $^{137}$Cs (Loughran, Pennock, & Walling, 2002);

• use of FRN conversion models for soil redistribution studies (Walling, He, & Appleby, 2002);

• specific use of $^{137}$Cs in Chernobyl-affected areas (Golosov, 2002), and

• $^{137}$Cs in situ measurements and $^7$Be and $^{210}$Pb$_{ex}$ methodologies (He, Walling, & Wallbrink, 2002).

5 | INCREASING THE SCOPE OF FRN USE

From 2002 to 2008, the CRP D1.50.08 "Assess the effectiveness of soil conservation techniques for sustainable watershed management using fallout radionuclides" was implemented as a follow-up of the first erosion CRP D1.50.05. Its main objective was to examine the possibility of using FRNs to evaluate the effectiveness of soil conservation measures and the overall impact of land use and land management on soil redistribution processes. Moreover, the intention was also to further develop the methodological aspects of FRN methods, especially the combined use of three FRNs with different half-lives: $^{137}$Cs (30.2 years), $^{210}$Pb$_{ex}$ (22.3 years), and $^7$Be (53.4 days) to study erosion over several temporal and spatial scales. Dercon et al. (2012) and IAEA (2011) summarized the findings of the CRP.

Two major achievements of the CRP were the establishment of standardized protocols for the use of all three radionuclides and the continuation of the development and the packaging of a new set of conversion models for all three radionuclides (Walling et al., 2002; Walling, Zhang, & He, 2011). This new set involved six improved models for $^{137}$Cs conversion as well as models adapted for the use of $^{210}$Pb$_{ex}$ and $^7$Be:

• proportional model;

• simplified mass balance model (MBM1);

• mass balance model 2 (MBM2);

• mass balance model including tillage aspect (MBM3);

• two models to investigate uncultivated sites (profile distribution model [PDM] and diffusion and migration model [DMM]);

• two models for using $^{210}$Pb$_{ex}$ at cultivated sites ($^{210}$Pb$_{ex}$ mass balance model [$^{210}$Pb$_{ex}$-MBM2] and $^{210}$Pb$_{ex}$ mass balance model that includes tillage aspect [$^{210}$Pb$_{ex}$-MBM3]);

• model for using $^{210}$Pb$_{ex}$ at undisturbed sites ($^{210}$Pb$_{ex}$-DMM), and

• model for using $^7$Be at cultivated and undisturbed sites ($^7$Be-PDM).

These models were combined into an Excel add-in, which is freely available from IAEA’s website (see http://www-naweb.iaea.org/nafa/swmm/soil-erosion-update.zip). A more refined $^7$Be model with extended time scale was developed later (Walling, Schuller, Zhang, & Iroumé, 2009). Walling et al. (2011) in their contribution to the IAEA TECDOC 1665 presented fully detailed information about each available conversion model, general guideline for selecting the proper model, and details on the parameters and the data requirement depending the FRNs to be used.

Aside from protocols and conversion models, the CRP D1.50.08 led the way to a number of other methodological achievements including fingerprinting of sediment sources at the watershed scale (Froehlich & Walling, 2005; Mizugaki et al., 2008; Onda et al., 2007; Rhoton et al., 2008; Ritchie, Nearing, & Rhoton, 2009; Zhang et al., 2004). Tiessen et al. (2009) pointed out how periodical (5–10 years) $^{137}$Cs sampling could be used to assess medium-term erosion. Belyaev, Golosov, Kuznetsova, and Markelov (2009) used Chernobyl and bomb-derived $^{137}$Cs to distinguish between soil redistribution rates associated with the pre-Chernobyl and post-Chernobyl periods. The soil redistribution rates estimated by FRN methods were compared with conventional measurements (Correchel, Bacchi, De Maria, Dechen, & Reichardt, 2005; Froehlich & Walling, 2005; Junge et al., 2010; Mabit et al., 2009; Mabit, Bernard, & Lavérdière, 2007; Schuller et al., 2006) and the results of modelling by Revised Universal Soil Loss Equation and Water Erosion Prediction Project (Bacchi, Reichardt, & Sparovek, 2003). The relationship of $^{137}$Cs inventories to major soil parameters such as soil texture and organic matter content was investigated (Li et al., 2006, 2007; Mabit & Bernard, 2010; Mabit, Bernard, Makhlof, & Lavérdière, 2008). Finally, a large number of case-studies were dedicated to the investigation of land use and land management impacts and the efficiency of conservation measures.

The D1.50.08 CRP brought also several findings on technical challenges, constraints, and limitations of FRN methods. One of the major challenges is the selection of a suitable reference site. In some areas, the problem can be caused by the high variability of rainfall (Belyaev et al., 2009), but in most cases, the problem originates from the lack of undisturbed land in steep mountains, densely populated regions, and intensively urbanized areas (Haciakyupoglu et al., 2005; Mabit et al., 2009). Other important limitations are low inventories of $^{137}$Cs in the Southern Hemisphere and high heterogeneity of $^{210}$Pb$_{ex}$ inventories (Belyaev et al., 2009; Mabit et al., 2009). Among the technical (analytical) challenges, variability in the capacity to measure $^{210}$Pb$_{ex}$ precisely was raised, as a proficiency test highlighted that only 31% of laboratories participating in the CRP achieved sufficient accuracy for $^{210}$Pb$_{ex}$ activity measurement (Shakhashiro & Mabit, 2009).

The major methodological principles and features of the FRN methods, as well as their advantages and limitations, were discussed in several papers (Mabit et al., 2013; Mabit, Benmansour, & Walling, 2008; Taylor et al., 2013; Zapata & Nguyen, 2009). However, some of these limitations and technical difficulties can be overcome by either more extensive sampling, to cover the variability (Mabit & Bernard, 2007; Mabit, Bernard, et al., 2008), or longer counting times to reduce error for low activity samples and more careful data interpretation.

6 | INTEGRATING SOIL AND WATER MANAGEMENT AT THE WATERSHED SCALE

For promoting their sustainable, natural resources should be managed in an integrated way at the watershed scale (IAEA, 2014).
Although some early work was undertaken in areas ranging from some hectares to a few square kilometres under D1.50.08 CRP and elsewhere, the need to develop more comprehensive watershed studies combining an oriented sampling strategy and a geostatistical approach, geographic information system, and $^{137}$Cs data set information (e.g., Mabit et al., 2007; Navas, Machín, & Soto, 2005) had already emerged.

Evaluating the magnitude of soil erosion over large areas is highly complex. Therefore, to gain better knowledge of sediment dynamic at watershed scale, there was a clear requirement to establish detailed area-wide sediment budgets (IAEA, 2014).

Scaling up the use of FRNs for assessing soil redistribution dynamic at the watershed scale was one of the key concepts investigated from 2009 to 2013 in the CRP D1.20.11 entitled “Integrated isotopic approaches for an area-wide precision conservation to control the impacts of agricultural practices on land degradation and soil erosion.”

The overall objective of this CRP was to establish an integrated isotopic approach to characterize critical areas of land degradation in agricultural watersheds so that targeted and efficient soil conservation actions could be implemented. In this context, CSSI techniques as well as other fingerprints were utilized in this CRP to trace sources of soil loss and sediment production for supporting the implementation of effective conservation agriculture.

FRN-based methods have been significantly improved during this CRP to provide information on sources, hillslope erosion, and sediment budgets. The requirement to upscale the application of FRN methods at the basin scale has necessitated the use of specific tools such as geostatistics to take into consideration the spatial variability of the landscape (IAEA, 2014; Walling & Zhang, 2010).

Following this CRP, one of the milestones of the SWMCN Subprogramme was the production of an up-to-date document summarizing experiences and knowledge of the IAEA and scientists involved in IAEA networks in using FRNs as soil redistribution tracers (IAEA, 2014). As commented by Porto (2016), it delivered clear step-by-step guidance on the three most used FRNs (i.e., $^{137}$Cs, $^{7}$Be, and $^{210}$Pbex) for soil redistribution investigations in agro-ecosystems.

Under this CRP, a harmonized protocol was also developed for the application of CSSI techniques using FAs as specific organic compounds, to localize sediment source and erosion hot spots at the watershed scale in a range of agro-environments (Gibbs, 2014). By linking fingerprints of specific land use to suspended or deposited sediment, CSSI techniques have proven to be a highly innovative approach for establishing the source of eroded soil or transported sediment. In addition, it is particularly useful for identifying areas delivering high sediment loads and thus contributing to water pollution (Gibbs, 2014; Heng, Sakadevan, Dercon, & Nguyen, 2014). CSSI-based techniques provide information on sources and can provide quantitative information as well as an additional dimension to generic source information that is more relevant to land use management decision making. However, this technique is still in its infancy with only a few published applied studies using specifically $^{13}$C of FAs to explore sediment transfer and origin within agro-ecosystems. Several aspects are still under investigation such as the best proxy or parameter to be used to convert isotopic signature into soil proportion.

As FRNs have proven to be powerful tools for assessing landscape-wide soil redistribution and identifying erosion processes, their integration with CSSI analysis opened new opportunities for improving area-wide soil conservation strategies for agricultural landscapes (Dercon et al., 2012; Heng et al., 2014). This CRP D1.20.11 focused on the integration of both complementary techniques as fingerprints and tracers of sediment redistribution within basins. A combination of FRNs, geochemistry (major and trace metals), and CSSIs can provide integrated information on erosion processes, spatial distribution, and land use of erosion sources. For instance, the use of $^{7}$Be, with a short half-life of 53 days, allows identification of recent sediment deposits, which can then be sampled for CSSI analysis so that hot spots of recent land degradation (sources and intensity of soil loss) can be identified. In addition, the coupling of FRNs such as $^{137}$Cs and $^{210}$Pbex with CSSI techniques showed how past land degradation and its link with land use history over the last centuries can be revealed (Gibbs, 2014). The combined uses of FRNs and CSSI have been tested successfully in Australia (Hancock & Revill, 2013) to identify hot spots and reassess previous understandings of landscape sediment dynamics (e.g., relative importance of channel bank erosion and other sources). Similarly, the combined use of CSSI and geochemistry has been used successfully to identify the importance of damaged pastures as erosion hot spots in the U.K. (Blake, Ficken, Taylor, Russell, & Walling, 2012).

In addition, an innovative and accurate sampling system, the Fine Increment Soil Collector, was developed at the SWMCN Laboratory to facilitate the precise determination of soil depth distribution of radionuclides (Mabit et al., 2014). Ryken et al. (2016) reported that the Fine Increment Soil Collector, compared with other existing sampling devices, allows for more precise collection of soil for erosion FRN-derived studies.

### 7 USE OF ISOTOPIC AND NUCLEAR TECHNIQUES TO ADDRESS SOIL EROSION IN THE CONTEXT OF CLIMATE CHANGE

In several regions across the globe, climate change is impacting the precipitation regime (Christensen et al., 2007), resulting in increased drought periods and high-intensity rainfall events (IPCC, 2013, 2014). As a result of climate variability and global warming, world average soil loss is predicted to further increase significantly (Li & Fang, 2016; Yang, Kanae, Oki, Koike, & Musiake, 2003). Soil erosion decreases soil productivity through soil, nutrient, and organic matter losses; deterioration of overall soil health; decrease of fertility, production potential, and biological activity; breakdown of soil structure; increase of soil erodibility; and reduction of soil water holding capacity. Poor soil quality further accelerates soil erosion, in particular on steep farmland, where this process is intensified by overgrazing and improper agricultural practices (McHugh, 2007; Tiwari, Sitaula, Bajracharya, & Borresen, 2009; Valentin et al., 2008). The intensification of upland erosion also increases sediment delivery downstream, causing further problems such as off-site erosion effects among which the most important is the siltation in water reservoirs and pollution of water sources and coastal sea waters resulting in the dying of coral reefs (e.g., Smith & Wilcock, 2015).

Upland agro-ecosystems are already under threat and will not be spared by this global phenomenon (Curtis, Battarbee, Monteith, &
Shilland, 2014; Destouni & Verrot, 2014). Indeed, they will face several challenges linked to food security and climate change (Beddington et al., 2012; FAO, 2013, 2017; HLPE, 2012).

In line with these statements, an expert meeting on “Soil and water conservation for climate change adaptation in agricultural uplands” was held in December 2014. This meeting paved the way for the new CRP D1.50.17 on “Nuclear techniques for a better understanding of the impact of climate change on soil erosion in upland agro-ecosystems” (2016–2021) that focuses on the refinement and development of isotopic techniques for improving our knowledge of the impact of climate variability on upland agricultural areas, so that better management can ensure sustainable production systems that will be resilient to the impacts of climate change.

A range of nuclear and isotopic techniques are being used to support these goals, including FRNs (\(^{137}\text{Cs}, \ ^{210}\text{Pb}_{\text{ex}}, \ ^{7}\text{Be}, \ ^{239+240}\text{Pu}\) and CSSI techniques as well as the cosmic-ray neutron probe. Combinations of these mature or innovative techniques are being tested as indicators of changes in soil and water resources occurring in fragile upland areas and for unravelling the relative importance of climate variability and agricultural practices.

Within this project, a newly proposed artificial FRN, that is, \(^{239+240}\text{Pu}\), is being further tested and validated as a soil redistribution tracer. The Pu isotopes have several advantages over the well-established \(^{137}\text{Cs}\) method, namely, a more homogenous spatial distribution that is unaffected by nuclear power plant accidents and a long half-life, which ensures a much longer environmental availability than that of \(^{137}\text{Cs}\) (Alewell et al., 2014, 2017; Hoo, Fifield, Tims, Fujioka, & Mueller, 2011; Lal, Tims, Fifield, Wasson, & Howe, 2013; Tims, Everett, Fifield, Hancock, & Bartley, 2010).

To differentiate the influence of climate variability and agricultural practices, paired catchment and FRN resampling approaches will be tested within the CRP activities. The paired catchment concept consists of investigating two small catchments of comparable size having similar geomorphological and climatic condition. One of these catchments may be mature or innovative techniques are being tested as indicators of changes in soil and water resources occurring in fragile upland areas and for unravelling the relative importance of climate variability and agricultural practices.

A FRN resampling option, using \(^{137}\text{Cs}\) (Loughran & Balog, 2006; Porto et al., 2014) or even \(^{210}\text{Pb}_{\text{ex}}\) as suggested recently by Porto, Walling, Cogliandro, and Callegari (2016), could be an easier and more valuable strategy for distinguishing and effectively apportioning the impact of climate change in upland agro-ecosystems. However, to test this approach in the context of the CRP and its specific objectives, it is mandatory (a) that the research is performed in an area already investigated with FRNs in the past, (b) that the lapse of time between the two FRN sampling campaigns is sufficient to notice significant changes of soil redistribution magnitudes (at least one decade after the first investigation is needed), and most importantly, (c) that the land use has remained the same since the first FRN investigation.

If all these assumptions—especially the latter—are respected, it can then be expected that only the climatic variability and its impact could explain a variation (if any) in the soil redistribution magnitude.

Since the start of the CRP D1.50.17, some preliminary and promising findings contributing to refining the FRN and CSSI techniques have already been obtained and published by participants of the CRP:

- the Department of Environmental Sciences (University of Basel, Switzerland) in collaboration with the SWMCN Laboratory developed a “universal” conversion model, called MODERN (i.e., Modelling Deposition and Erosion rates with RadioNuclides), to assess soil redistribution magnitudes from FRN measurements (Arata et al., 2016). MODERN is the only conversion model that can be used for \(^{137}\text{Cs}, \ ^{210}\text{Pb}_{\text{ex}}, \ ^{7}\text{Be}\) as well as for the new soil tracer \(^{239+240}\text{Pu}\);
- plutonium isotopes (i.e., \(^{239+240}\text{Pu}\)) have been tested and validated relative to other more mature radiotopic approaches for deriving soil erosion rates under various upland agro-environments in Switzerland (Arata et al., 2016; Meusburger et al., 2018) and also in South Korea (Meusburger et al., 2016);
- the development of a cost-effective sampling strategy when using CSSI techniques to reduce and optimize analytical labour (Mabit et al., 2018), and the use of artificial mixtures to confirm the accuracy and reliability of the CSSI mixing models, a new proposal for converting isotopic proportion into soil proportion using the FA concentrations instead of the total % Corg has been made (Alewell, Birkholz, Meusburger, Schindler Wildhaber, & Mabit, 2016);
- through their studies in South West England, Taylor, Keith-Roach, Iurian, Mabit, and Blake (2016) reported that the use of cosmogenic \(^{8}\text{Be}\) as a soil erosion and/or sediment tracer requires an accurate knowledge of its temporal fallout dynamics as its deposition flux can be highly variable across months and seasons;
- a study performed in the Madagascar highlands (see next section) highlighted that the combined use of \(^{137}\text{Cs}\) and \(^{210}\text{Pb}_{\text{ex}}\) allowed evaluating the effectiveness of ancient terracing practices to protect soil against erosion. For the first time, this pilot Malagasy FRN investigation highlighted that despite low expected \(^{137}\text{Cs}\) activity, this method can still be used with success in African countries located in the Southern Hemisphere. The suitability of \(^{210}\text{Pb}_{\text{ex}}\) as a soil tracer under Malagasy agro-climatic condition was also verified and provided similar results to those obtained with \(^{137}\text{Cs}\) (Rabesiranana, Rasolonirina, Solonjara, & Mabit, 2016).

8 | USEFULNESS OF THE FRN TECHNIQUES: EXAMPLES OF SELECTED AFRICAN AND ASIAN COUNTRIES IMPACTS

The results of CRPs are further disseminated through Technical Cooperation Projects to IAEA Member States. Most of these demands come from agricultural research and governmental soil conservation programmes with needs to assess erosion rates, and impacts of land use changes and land management with regard to erosion and sedimentation processes. Other requests come from water management authorities and organizations interested in preventing siltation in water reservoirs. The benefits resulting from application of nuclear techniques in soil erosion and sedimentation can be illustrated by the following case studies.
8.1 Assessing the effectiveness of terraced agriculture in Madagascar’s agricultural highlands through the use of FRNs

Soil degradation—mostly due to soil erosion—is of national concern in Madagascar. According to the FAO, around one third of the island’s total soil area is degraded (Nachtergaele et al., 2011). To establish effective conservation strategies, trustworthy rates of soil erosion/sedimentation under different Malagasy land uses are required.

In partnership with the “Institut National des Sciences et Techniques Nucléaires” (INSTN—Madagascar) based in Antananarivo, the SWMCN Subprogramme investigated soil erosion problems in order to strengthen the resilience and ability of the Malagasy smallholder farmers to ensure food security. Thus, for the first time, fallout $^{137}$Cs and $^{210}$Pb$_{ex}$ methods were tested effectively in Madagascar with the objective of investigating the effects of traditional agricultural practices utilized on hillslopes (Rabesiranana et al., 2016).

Soil erosion rates of an unprotected agricultural field and a terraced field were quantified in an experimental study area located in the eastern central highlands, 40 km east of Antananarivo (Photo 1).

As reported by Rabesiranana et al. (2016), this pioneer use of FRNs (i.e., $^{137}$Cs and $^{210}$Pb$_{ex}$) demonstrated that, in promoting the use of traditional terrace systems, soil erosion can be reduced by up to 40%. This Malagasy study also highlighted that traditional terracing could significantly limit the transfer of sediment and therefore the downstream potential off-site impact of the agro-ecosystems in allowing a better soil redistribution within the agricultural fields.

8.2 FRN techniques contribute to the improvement of soil conservation in Moroccan agro-ecosystems

In Morocco, reducing on-site and off-site impacts associated with soil erosion and land degradation is a major concern for improving soil quality and protecting downstream water quality and quantity. Soil erosion is the main land degradation process in Morocco and affects at least 13% of its land area (Nachtergaele et al., 2011).

In partnership with the SWMCN Subprogramme, the Centre National de l’Énergie des Sciences et Techniques Nucléaires (CNESTEN) and its local Moroccan partners investigated soil degradation using FRN techniques (i.e., $^{137}$Cs and $^7$Be) to contribute directly to agricultural decision making at the national level.
Case studies using $^{137}$Cs and $^{7}$Be were carried out in three Moroccan agricultural sites—Marchouch, Harchane, and Oued Mellah—which are located respectively in the regions of Rabat, Tétouan, and Chaouia-Ouardigha. Long-term soil erosion rates of the three regions as evaluated by the $^{137}$Cs method ranged from 8 to 58 t·ha$^{-1}$·year$^{-1}$ (Benmansour et al., 2013). For the experimental sites in Rabat and Tétouan, the results obtained using $^{7}$Be indicated that soil losses have been reduced appreciably under no-till as compared with conventional tillage. Thus, by adopting no-tillage soil conservation practices, soil loss from Moroccan watersheds can be diminished by approximately 40%, leading to a significant reduction of sedimentation into reservoirs. In the Oued Mellah watershed, high-density Atriplex plantations reduced soil loss by approximately 60% to 80%, whereas soil erosion decreased by 58% on sites with fruit plantations plus cereals.

8.3 FRNs as decision-making tools to minimize land degradation in Vietnam

Lowland agricultural areas are scarce in Vietnam due to increasing population growth. Thus, there is an increasing cultivation pressure on the Vietnamese sloping lands, which is causing severe soil degradation, leading to a significant reduction of soil fertility. Approximately 40% of Vietnam’s total land area is affected by soil erosion (Sanh, 2006). To compensate for nutrient losses associated with erosion processes, high levels of chemical fertilizers (>250 kg·ha$^{-1}$) are being applied to maintain current crop yields (Hai & Dung, 2014). The SWMCN Subprogramme in collaboration with researchers from the Centre for Environment Research and Monitoring, the Nuclear Research Institute, the Vietnam Atomic Energy Institute, and the Ministry of Science and Technology assessed soil erosion rates from a land area of about 10,000 km$^2$ in the province of Lamdong, in the southern part of the Central Highlands of Vietnam (Photo 2). FRN techniques such as $^{7}$Be and $^{137}$Cs were used for quantifying soil erosion rates at 27 different study sites representing a wide range of slopes. Prior to adopting soil conservation measures, the annual soil erosion rates ranged from 12 to 42 t·ha$^{-1}$·year$^{-1}$ for different land slopes, with a magnitude above 40 t·ha$^{-1}$·year$^{-1}$ observed on 25° to 35° slopes. These high soil erosion rates led to significant losses of organic matter and essential plant nutrients. For example, annual organic matter losses of 555, 840, and 1,200 kg·ha$^{-1}$ were recorded for slopes of 5° to 15°, 15° to 25°, and 25° to 35°, respectively. However, by using effective soil conservation measures, eroded areas were significantly reduced. For example, in areas with a slope of 25°, by intercropping pineapple with cashews, the yearly soil loss was reduced from 42 to 27 t·ha$^{-1}$, relative to pineapple monoculture. On slopes of 18° to 20°, contour farming, compared with the control for tea plantations, decreased soil erosion rates by 36%. Similarly, for tea plantations on slopes of 8° to 10° where 1.4-m contour lines were utilized, soil erosion was reduced by 40% (i.e., 24 compared with an original 34 t·ha$^{-1}$·year$^{-1}$ for the untreated slopes). For coffee plantations, by creating miniature catchment basins at the base of each coffee plant, soil erosion decreased by 42% compared with that of the untreated control (16 compared with 28 t·ha$^{-1}$·year$^{-1}$). For mulberry fields, contour farming together with intercropped maize was even more effective, with soil loss decreasing by 54% (11 compared with 23 t·ha$^{-1}$·year$^{-1}$). For vegetable fields, by the use of terraced farming on slopes of 7° to 10°, the soil erosion rate decreased by 59% (7 compared with 17 t·ha$^{-1}$·year$^{-1}$). Preliminary tests using CSSI techniques have
highlighted the fact that coffee plantations without soil conservation measures were the major source of eroded soil in the study area. Assuming that the 13 million ha of sloping lands in Vietnam contain 1% soil organic matter (presuming a 5% nitrogen and 0.5% phosphorus content) and that the average soil erosion rate is 25 t·ha⁻¹·year⁻¹, then a 47% reduction in soil erosion will allow the retention of soil nitrogen and phosphorus with estimated fertilizer cost values of U.S. $55 million for nitrogen and US $19 million for phosphorus.

9 | CONCLUSION

During the last 20 years, the Joint FAO/IAEA Division, through various activities conducted by the SWMCN Subprogramme, has significantly contributed to the development and refinement of efficient isotopic techniques to localize degraded agricultural areas, to evaluate soil redistribution magnitudes from field to watershed scales, to assess the effectiveness of soil conservation strategies, and, more recently, to establish the origin of the mobilized and deposited sediment.

Complementing conventional soil erosion measurement methods and modelling, FRN and CSSI techniques have deepened our understanding of soil erosion and its related agro-environmental impacts. The SWMCN Subprogramme has disseminated, implemented, and/or supported their use in more than 70 countries, particularly through the IAEA’s Technical Cooperation Program resulting in the production of several national impact stories such as the ones obtained in Morocco, Madagascar, and Vietnam.

The Joint FAO/IAEA Division has, to some extent, succeeded in promoting the transition of nuclear and isotopic techniques from a validated research tool to a decision support tool. Scope for improvement remains in reinforcing the accuracy of these techniques and refining some operational parameters, but scientific evidence has demonstrated that the combined use of stable and radioisotopic tracers provides crucial information to guide decisions on the management of critically degraded areas and may support land managers to implement appropriate soil conservation measures at these hot spots. This will ultimately result in the improved efficiency of soil and water resource management, higher economic returns, and agro-environmental sustainability in the face of climate change.

This way, the work, both past and present, undertaken by the SWMCN Subprogramme has strongly contributed to the achievement of several of FAO’s strategic objectives as well as the UN’s Millennium Development Goals.

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ORCID

Lionel Mabit http://orcid.org/0000-0001-9346-3845

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