Complementary use of geo-chemical fingerprints and fallout radionuclides to evaluate the impacts of livestock and agricultural practices on soil erosion processes in a semi-arid region of central Argentina

ROMINA TORRES ASTORGA (1)(2), YANINA GARCİAS (1), MARCOS RIZZOTTO (1)(2), GISELA BORGATELLO (1), LIONEL MABİT (3) & HUGO VELASCO (1)(2)

(1)IMASL / UNSL / CONICET - Av. Ejército de los Andes 950, San Luis, Argentina
e-mail: rtorres@unsl.edu.ar
(2) Departamento de Física, Universidad Nacional de San Luis-CONICET. Ejército de Los Andes 950, San Luis, Argentina
(3) Soil and Water Management & Crop Nutrition Laboratory, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Department of Nuclear Sciences and Applications, International Atomic Energy Agency, Vienna, Austria

ABSTRACT

This study focuses on the complementary application of two innovative techniques: a) the use of geo-chemical elements as fingerprints to investigate sediment transport and b) to compare the values of 137Cs soil inventory in an Argentinian site with respect to the local reference value to quantify erosion or sedimentation processes (137Cs technique). The main aim is to evaluate the impacts of land degradation due to agricultural practices implemented in recent decades in a semi-arid region of the Province of San Luis in Central Argentina. Phosphorus, iron, calcium, barium, and titanium as well as the total organic carbon content were applied for identifying critical hot spots of erosion in the studied catchment. Feedlots were identified as one of the main sources of sediments together with river banks, dirt roads and livestock grazing. Additionally, the comparison of 137Cs soil inventory in agricultural sites versus an undisturbed reference site (330 Bq m⁻² (SD: 54 Bq m⁻²)) highlighted that the agricultural practices, based on direct seeding without plowing, constitutes an advisable practice to minimize the loss of surface soil.

Keywords: Hot spots of erosion, XRF, 137Cs, land uses.

1 INTRODUCTION

Soil erosion reduces significantly cropland productivity and contributes to pollution of water-courses, wetlands, and lakes. This natural process becomes even more critical in arid and semi-arid zones (as the west-centre of Argentina) due to two main reasons: (i) agricultural areas were expanded at expenses of native forest cover, disturbing the hydrological balance, and (ii) associated with climate change, precipitations show a tendency to increase, with a higher frequency of extreme rainfall events (Barros et al., 2015; Giménez et al., 2016; Manyevere et al., 2016). Therefore, in order to implement effective strategies for controlling excessive flow of sediment, it is necessary to determine the nature as well as the location of the main sources of sediments at watershed scale. Sediment geochemistry has been widely used to identify the spatial sources of sediments delivered to watercourses (Hardy et al., 2010). Fingerprint techniques allow the identification and quantification of transported sediment from different sources. The geochemical concentrations of eroded sediments are mainly conditioned by the type of soils and the geological substratum from which they originate (Blake et al., 2012). Applying mixing models (MM) allow to determine the relative contributions of different sources to the sediment mixtures in the fate places on the water courses. Mass concentration of geochemical element of soil can be assessed by energy dispersive X-ray fluorescence (EDXRF) spectroscopy (see (Melquiades et al., 2013)).

On the other hand, the use of fallout radionuclides (FRNs) has proven to be an effective approach for establishing erosion and sedimentation magnitudes within various agricultural landscapes (Zapata, 2002; Mabit et al., 2014). After their atmospheric fallout, FRNs are rapidly and strongly adsorbed by the top soil and then their spatial pattern at the land surface reflects the transport and deposition of soil and sediment particles (IAEA, 2014; Mabit et al., 2008).

137Cs is an anthropogenic FRN, with a half-life of 30.2 years, which can be found worldwide as consequence of the worldwide atmospheric thermonuclear weapon tests that took place during the period extending from the mid-1950s to the mid-1960s. 137Cs can provide retrospective information on medium-term soil erosion (50-60 years) (Zapata, 2002). The global 137Cs fallout levels were variable, reflecting both annual precipitation amount and location relative to the previous main weapon tests (Walling and He, 1999). In the explored region, the reference inventory of 137Cs was established at 330 Bq m⁻² (SD: 54 Bq m⁻²). A transect of
735 m length, following the slope direction, was investigated in the agricultural study site with the purpose of comparing the $^{137}$Cs inventory with the value obtained at the reference site. A total of 7 sampling points was selected along that transect. The $^{137}$Cs inventory ranged from 250 Bq m$^{-2}$ to 570 Bq m$^{-2}$.

The specific objectives of this investigation were: i) to use geo-chemical elements as soil tracers to identify the origin of the sediments and ii) to establish a reliable inventory value of fallout $^{137}$Cs for quantifying the variation of the $^{137}$Cs soil content along a slope of a typical agricultural field.

2 MATERIALS AND METHODS

2.1 Study region: El Durazno Sub-catchment

Figure 1. Location of the studied region in South America.

El Durazno Sub-catchment (previously called Estancia Grande Sub-catchment), is located in a semiarid zone of central Argentina (S 33°10'; W 66°08'), 23 km north-east of San Luis City (Province of San Luis) at 1100 meters a.s.l. The area of the studied sub-catchment is 1235 ha. Average annual temperature is 17 °C. Annual rainfall ranges from 600 to 800 mm, with a tendency to increase in the last years. Rainfall varies seasonally, with a dry season from May to October and a rainy season from November to April. Rains in the dry season are scarce and sporadic, with occasional drizzles. Soils are dominated by Haplic Kastanozems. In the basin, the expanded deforested area is used for agriculture (rotation crop), livestock (free grazing and feedlots) and some fields are used for growing nuts trees (walnuts and almonds). In the mid and south part of the sub-catchment the river banks have develop long vertical walls up to 6 m height and the number of gullies increases. The studied area includes as well dirt roads used for transportation of goods and inhabitants of the area.
2.2 Sampling procedures

For geo-chemical elements fingerprints identification, the sampling procedure involved removing the leaves and plant material before taking a soil layer of 100 cm² and 2 cm thick of exposed soil using a stainless-steel flat spatula. At each location, multiple subsamples from an area of about 100–200 m² were collected in a plastic bucket to obtain a composite sample representative of that land use (source samples). For the sediments samples (mixtures) of the river course, the samples were collected at the top 20 mm of the accumulation zones on little floodplains where deposition process was observed. The sediment samples were taken during three different periods: (1) end of rainy season (2) end of dry season, and (3) middle of rainy season.

For the use of 137Cs as an indicator of surface soil loss, a flat area of about 400 m² (33°10'46.05" S; 66°08’24.81″ W) was identified as a potential undisturbed reference site (RS). In this area, a rectangular sampling grid with 15 (3x5) sampling points was adopted (Figure 4). The spacing between points was 7 m x 5 m. At each sampling point, metal cores tubes of 5 cm diameter were inserted manually into the ground using a hammer and removed with a steel lifting jack, which includes a lever and chain system for performing the extraction process. In the field, for 5 points at RS, 4 soil cores were extracted from every point and cut in 3 cm thick layers, from the surface to a depth of 30 cm. For the rest of the sampling points (10 out of 15), 2 soil cores were collected at each point, soil samples were cut into 2 layers: 0-18 cm and 18-24 cm. At each sampling point, incremental samples from the same soil layer were combined to obtain composite single sample.

At the agricultural study site (33°10'28.94" S; 66°07’51.91” W), a transect of 735 m length was investigated following the slope direction. In this transect seven sampling points were performed, the distance between the points was almost equidistant (i.e. 100 m), trying to avoid the local topography anomalies. Samples were collected following the same experimental approach adopted at the reference site. In each sampling point of the transect, the soil cores were collected within an area of 1 m², avoiding any disturbance between samples. In 6 out of 7 points, the cores were cut in 0-9 cm, 9-13.5 cm, 13.5-18 cm and 18-24cm layers. When sedimentation was suspected an extra layer was collected from 24 to 30 cm. In the remaining point, the soil core was cut in 3 cm layers from the surface to a depth of 30 cm to study the vertical distribution of 137Cs along the soil profile.
2.3 Geo-chemical element fingerprints

EDXRF spectrometry analysis was performed for source and mixtures samples. The samples were ground into fine powder, which was used to produce pressed pellets of 25 mm diameter and 2.5 g weight. The pellets were measured at the Nuclear Science and Instrumentation Laboratory (IAEA Laboratories, Seibersdorf, Austria), using a 10 targets EDXRF spectrometer (Epsilon 5 by PANalytical). Elemental concentrations of more than 50 elements in each sample were measured. Fingerprints were selected applying Kruskal Wallis H test, Discriminant Function Analysis and Bi-plots examination. These fingerprint elements were validated using two artificial mixtures (Torres Astorga et al., 2018), CSSIAR v2.00 (de los Santos-Villalobos et al., 2017) and IsoSource (Phillips and Gregg, 2003) were applied for identifying critical hot spots of erosion using the selected geochemical elements and total organic carbon (TOC) of the sources and mixture samples.

2.4 $^{137}$Cs measures in soil samples

After classical pre-treatment (air drying at 105° and sieving at 2 mm) (IAEA, 2014), the $^{137}$Cs activity measurements of all soil samples from the RS and the agricultural site were performed at the GEA-IMASL Gamma Spectrometry Laboratory using an extended range p-type HPGe Canberra detector, model GX4018, with a relative efficiency of 40 %, energy range 10 keV – 10 MeV, 0.925 FWHM at 122 keV and 1.8 195 FWHM at 1.3 MeV, peak to Compton ratio 62, 1.90 FWTM/FWHM. The spectrometer is shielded by a 100 mm thick low background lead shield (Canberra Model 747 top opening, 406 mm deep, 279 mm diameter).

3 RESULTS AND DISCUSSION

3.1 Fingerprinting of sediments

Hot spots of land erosion were previously determined using as fingerprints of land uses the geochemical elements: Ba, Ca, Fe, P and Ti (Torres Astorga et al., 2018). The resulting proportions for the 5 mixture samples collected in the river course are shown in the figure 3. In the 2 northern mixtures (i.e mixture 4 and 5) TOC was used as an additional fingerprint increasing the precision of the resulting proportions without appreciable changes in the means. In every chart of figure 3, the different contributions for sediments collected in the three periods of time ((1) end of rainy season (2) end of dry season, and (3) middle of rainy season) are shown as a bar. For mixture 4 and 5, the sediments were collected in two of these periods, (2) and (3).
Figure 3. Sediment apportionment in the five river sediment mixtures. Mixtures were collected at (1) the end of rainy season, after harvesting; (2) the end of dry season; (3) middle of rainy season.

3.2 $^{137}$Cs technique.

a. Reference site selection

Very close to El Durazno Sub-catchment a flat and undisturbed plot of soil was identified. In this area a grid sampling was performed and the $^{137}$Cs inventories of these points are shown in figure 4.

The average inventory in the RS was 330 Bq m$^{-2}$ at the sampling date (2016), with a standard deviation of 54 Bq m$^{-2}$, which results in a 16% coefficient of variance (CV) (Table 1). The $^{137}$Cs inventory obtained in this site is close to the value estimated by a popular add-in (Walling et al., 2011), which is 400 Bq m$^{-2}$ for an annual average precipitation of 800 mm. The reference site has a CV lower than the mean of similar studies (Pennock, 2000) which demonstrates the reduced soil disturbance in the site.
Table 1. $^{137}$Cs parameters at the reference site

<table>
<thead>
<tr>
<th>137Cs</th>
<th>Inventory (Bq m$^{-2}$)</th>
<th>Standard Deviation (SD)</th>
<th>Coefficient of Variance (CV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>330</td>
<td>54</td>
<td>16%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. $^{137}$Cs inventories (Bq m$^{-2}$) in each sampling point of the grid in the RS. Differences in the cells’ brightness are according to the range of values.

Table 2. $^{137}$Cs inventories at the study site

<table>
<thead>
<tr>
<th>$^{137}$Cs Inventory (Bq m$^{-2}$)</th>
<th>$^{137}$Cs SD Inventory (Bq m$^{-2}$)</th>
<th>Relative difference with the RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 284</td>
<td>54</td>
<td>-14 %</td>
</tr>
<tr>
<td>P2 571</td>
<td>85</td>
<td>73 %</td>
</tr>
<tr>
<td>P3 262</td>
<td>40</td>
<td>-21 %</td>
</tr>
<tr>
<td>P4 408</td>
<td>47</td>
<td>24 %</td>
</tr>
<tr>
<td>P5 357</td>
<td>50</td>
<td>8 %</td>
</tr>
<tr>
<td>P6 253</td>
<td>47</td>
<td>-23 %</td>
</tr>
<tr>
<td>P7 338</td>
<td>43</td>
<td>3 %</td>
</tr>
</tbody>
</table>

b. Study site: agriculture with direct seeding

In a field of crop cultivation, a transect sampling was completed in 2017. The $^{137}$Cs inventories in the 7 sampling points can be seen in table 2. The relative differences between these values and the reference one ($330 \pm 54$ Bq m$^{-2}$) can be found in the mentioned table as well. The variability observed in the $^{137}$Cs inventories at the points along the transect (with their uncertainties) do not differ much from the inventory values found at the reference site ($350 \pm 110$ Bq m$^{-2}$). On average, the study site inventory is very close to the reference inventory, although the variability at the study site is greater ($CV=31\%$). The deposited amount of $^{137}$Cs in the study area seems to have not suffered great losses. The greater variability observed in the $^{137}$Cs inventory in the agricultural site with respect to the reference site could be attributed to the consequences of the farmers’ activities (e.g. sowing procedures, the transit of people, vehicles and machines). Variability in the $^{137}$Cs soil content is compatible with movements of sediments in low proportion, inside the cultivated area, without a clear pattern that can be identified. These evidences indicate that sediment displacement towards the site is minimal.

4 Conclusions

A geochemical fingerprinting technique has been performed in a 12 km$^2$ sub-catchment located in a semi-arid region of Argentina. The validation of the selected fingerprint elements was made through two artificial mixtures of known proportions. The application of the fingerprinting technique highlighted that feedlots are the one of mayor sediments contributors, followed by the banks and dirt roads. On the other hand, rotation crop fields and native vegetation soils seem to be minor sediment contributors. In fact, when analysing $^{137}$Cs content in a rotation crop field, we found similar contents than at the reference site. From this FRN preliminary study, we obtained the following results:

I. There is a high variability in the content of $^{137}$Cs at the study site. Probably, the seeding and cultivation, the machinery and the transit of people contribute to this variability.
II. The method used does not allow quantifying precisely if there has been loss of surface soil since the $^{137}\text{Cs}$ fallout in the region. The inventory at each sampling point, based on the uncertainty and the observed variability, is comparable to the inventory calculated at the reference site. Considering the confidence intervals, most of the inventories in the study site are the same than at the reference value.

IV. The agricultural practices developed in the study site do not seem to generate important erosion processes.

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