University of Puerto Rico, Mayagüez Campus
Department of Agricultural and Biosystems Engineering

Proximal and Remote Sensing Approaches to Sediment Tracing in Tropical Environments

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Introduction

- ***Soil erosion*** is a major problem that affects ***ecosystem sustainability***, particularly in ***tropical regions*** with high levels of precipitation.

- Soil erosion can lead to:
  - ***loss of cultivable land***,
  - ***decreased soil fertility***,
  - ***increased food production costs***,
  - ***negative impacts on water quality and availability***,
  - ***biodiversity loss***, and
  - ***decreased ecosystem resilience***.

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Research Background

- To identify the sources of sediments in drainage basins, researchers have used *"fingerprinting"* techniques to track unique substances or elements in the sediments *(e.g.,* cluster analysis to group data with similar characteristics).
- Most *fingerprinting* studies have been conducted in large catchment areas adding tracers (*e.g.*, radioactive isotope Cs-137, Rare Earth Materials).
- Using small drainage basins as a unit of study has proven to be a reliable method for understanding the interactions between human activities and erosion processes.
- Applying the *fingerprinting* technique in smaller basins and small plots may be a more cost-effective and accurate alternative to validate the use of emerging technologies.

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What for?

- Sediment source determination identifies watershed areas that contribute the most to erosion, providing information into sediment transport dynamics.
- This information can be used for decision-making regarding soil and water management.
- Adequate soil and water management helps protect water quality and supports sustainable land use.

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Overall Objective

To identify and quantify the contribution of different sediment sources within the watershed by integrating remote and proximal sensing with soil and sediment fingerprinting using a portable X-ray fluorescence spectrometer (pXRF) and data modeling techniques.

Scope for 1st Experiment (Brazil)

- In this study, the portable X-ray fluorescence spectrometer (pXRF) and the magnetic susceptibilimeter were used to analyze sediments in a drainage subbasin in Brazil.
- The hypothesis was to test whether the source of deposited sediments can be identified using proximal sensors in small drainage basins.
- These portable sensors make data acquisition efficient and minimize the need for soil sample collection and chemical reagents.
- The study aimed to use the *fingerprinting* technique with proximal sensors to identify the source of deposited sediments in the lower portion of the subbasin.

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Area of Study

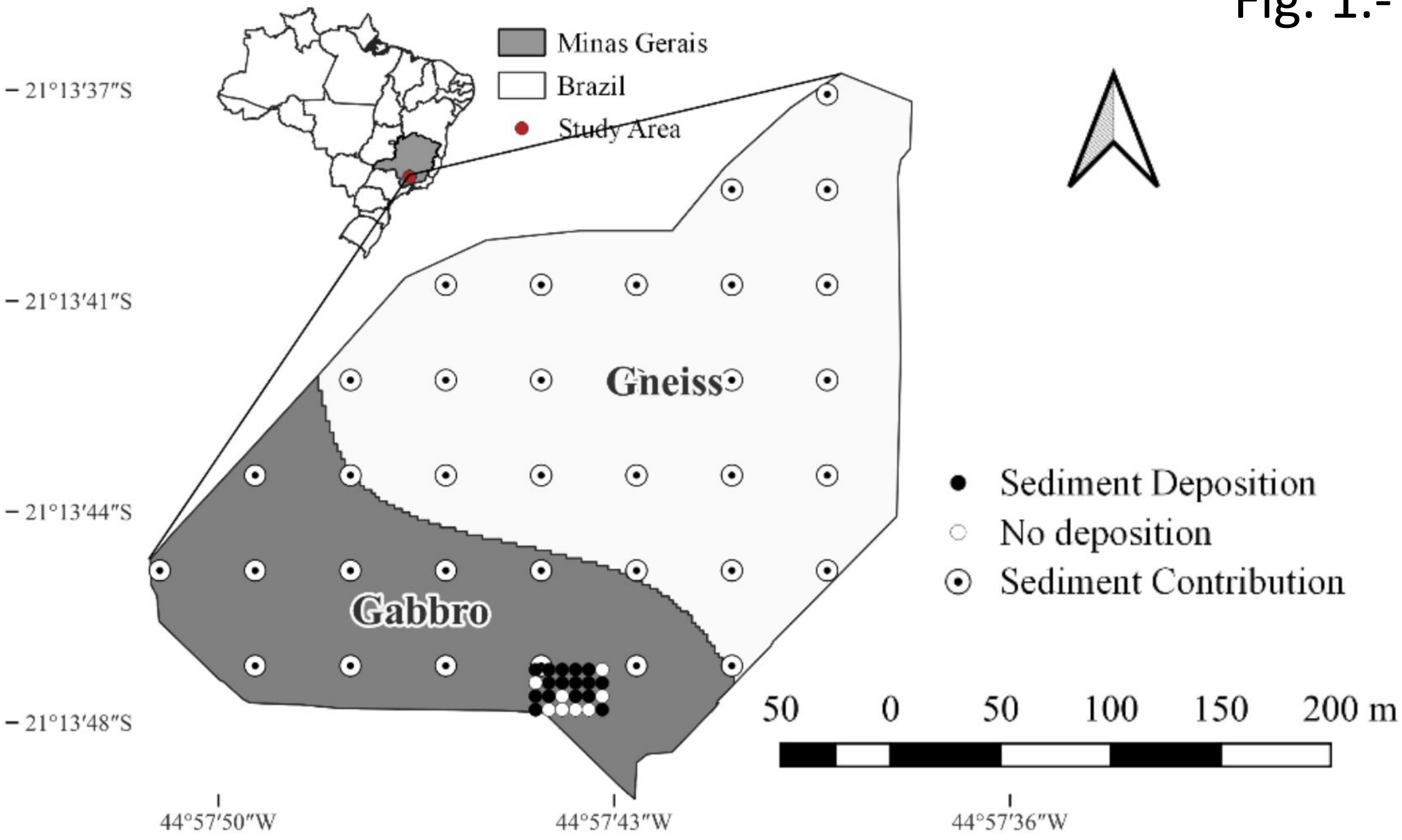
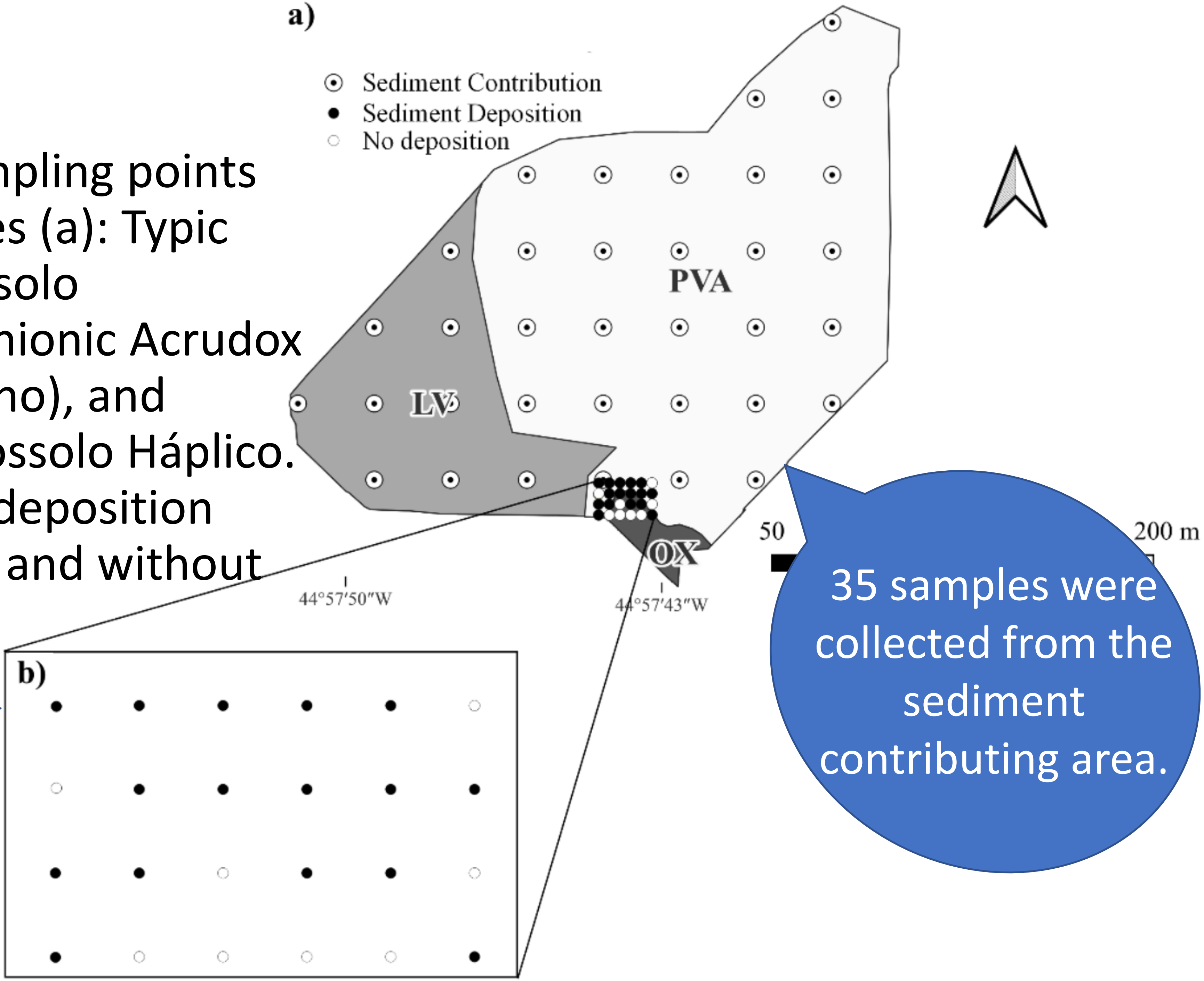


Fig. 1.- Drainage subbasin (8.71 ha) situated in Lavras, Minas Gerais, Brazil. Parent material map and sampled points in the lower deposition area (with and without sediment deposition).

Fig. 2.- Study area and sampling points organized by soil classes (a): Typic Hapludult (PVA – Argissolo Vermelho-Amarelo), Anionic Acrudox (LV – Latossolo Vermelho), and Udifolists (OX – Organossolo Háplico. Sampled points in the deposition area are depicted with and without sed

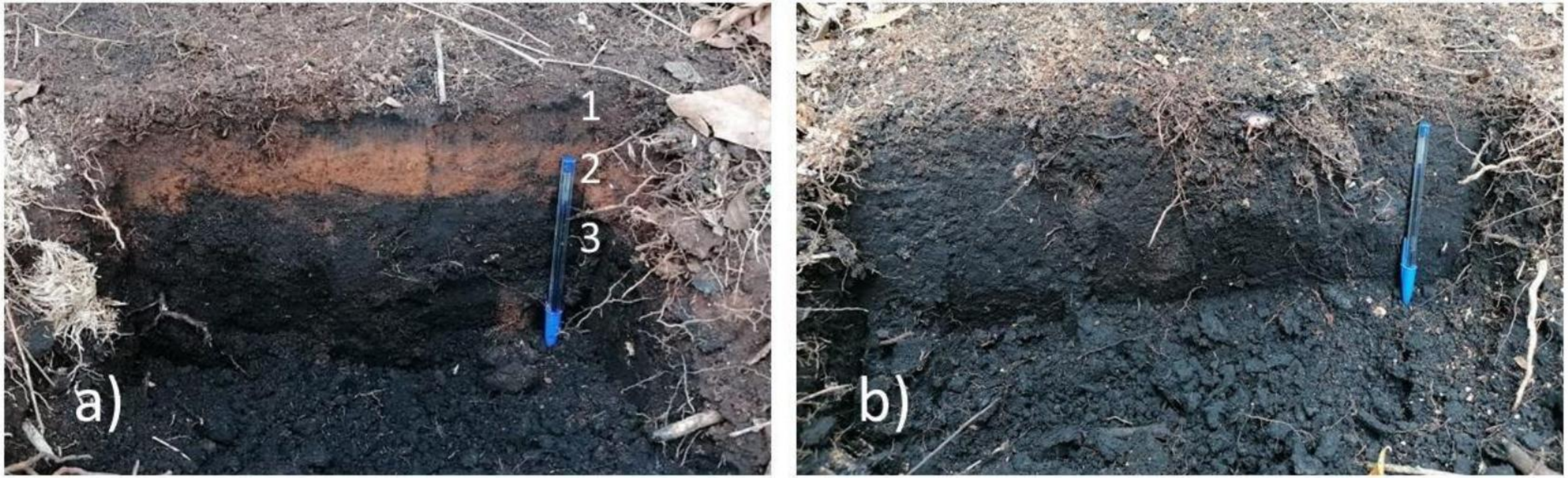


24 samples were collected from the sediment deposition area.

35 samples were collected from the sediment contributing area.

Soil Sampling and Lab Analyses

1. Soil samples were collected using non-metallic tools.
2. Samples were air-dried, sieved, and packed in polyethylene bags with 20 μm thickness.
3. The depth of the deposited material was also measured.
4. pXRF and magnetic susceptibility measurements were performed under lab conditions.



Data Processing and Statistical Analyses

- Elemental contents of Fe, Si, Al, Ti, and Zr were selected as tracers to help identify the origin of sediment deposits.
- Magnetic susceptibility (MS) was also used to help differentiate minerals based on their magnetic properties.
- The contribution of different areas to the sediment deposits was identified through relief analysis and cluster analysis.
- The K-means method was used in cluster analysis to classify samples of deposited sediments and samples from contributing areas based on selected elements.
- The analysis was conducted using the R software and the caret package, with *K*=3, *iter.max*=10, and *nstart*=50 as parameters.

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Results

Table 1.- Elemental contents of tracing elements via pXRF and measured magnetic susceptibility of two soils in a drainage subbasin located in Lavras, Minas Gerais, Brazil.

	Anionic Acrudox (LV)			Typic Hapludult (PVA)		
Element or Property	Max.	Mean	Min.	Max.	Mean	Min.
Al (%)	14.61	12.36	10.50	16.91	13.68	10.79
Fe (%)	14.60	11.73	7.93	10.51	7.38	4.97
Si (%)	7.28	6.14	4.72	13.06	8.53	6.02
Ti (%)	0.73	0.61	0.48	0.71	0.58	0.42
Zr (%)	0.03	0.02	0.02	0.03	0.02	0.02
MS (10^{-7}.m^3.kg^{-1})	**81.42**	**63.28**	**27.25**	**59.35**	**20.52**	**5.46**

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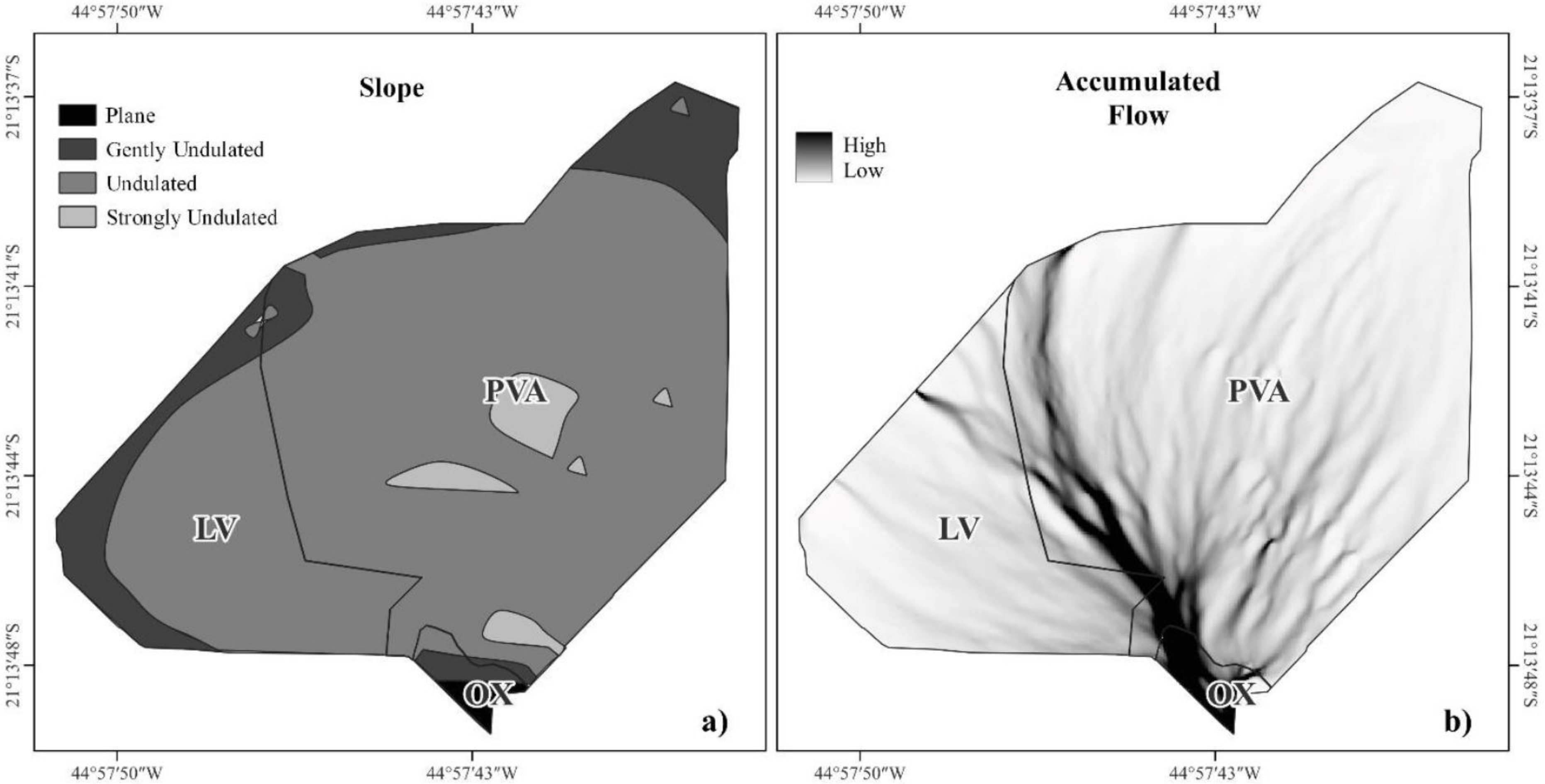
Relief Analysis

Fig. 4.- Slope classes (a) and flow accumulation (b) maps depict the landscape traits. Therefore, it was expected that PVA would contribute the most with sediments.



Typic Hapludult (PVA)

Anionic Acrudox (LV)

Udifolists (OX)

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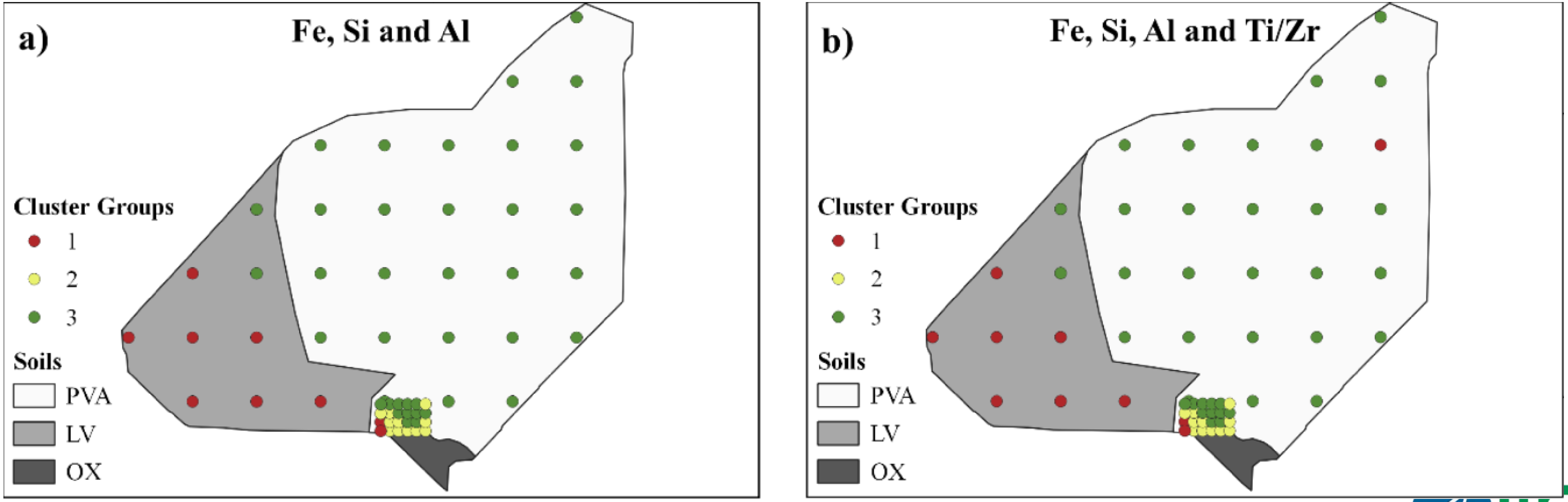
Cluster Analyses

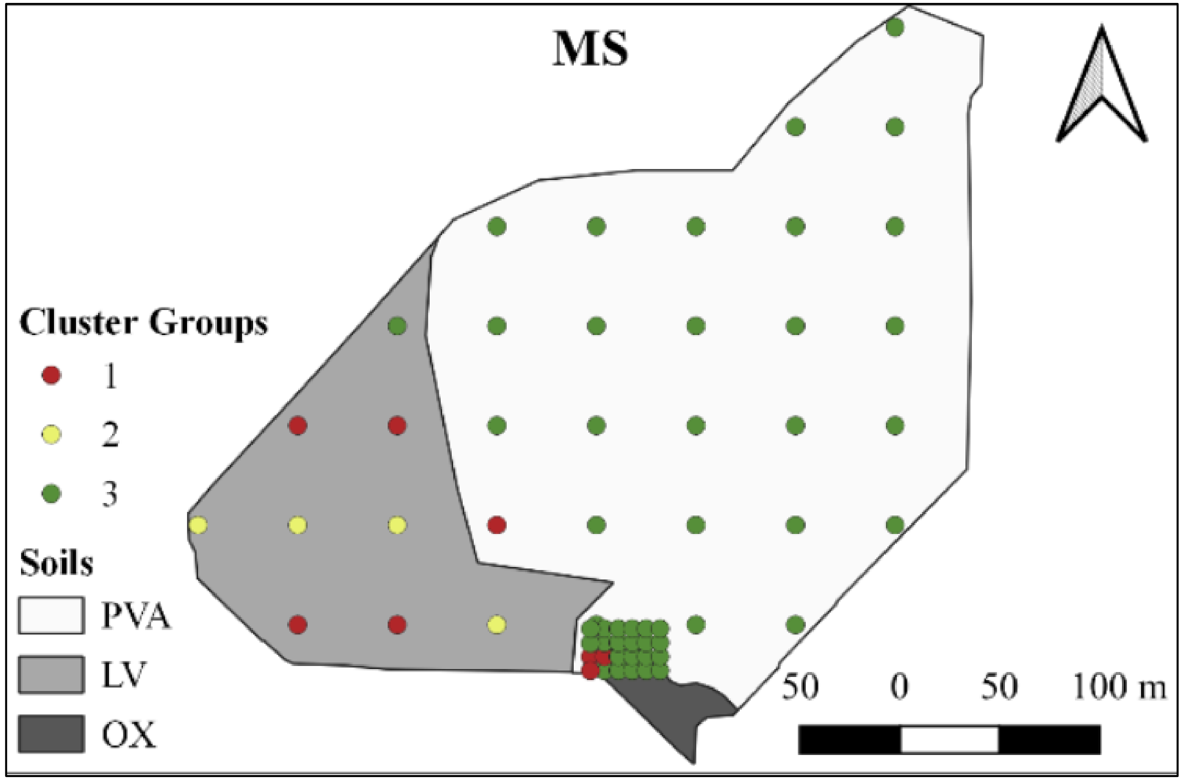
Fig. 5.- Maps classified by cluster analysis using sediment tracing elements Fe, Si, and Al (a); and Fe, Si, Al, and Ti/Zr (b) presented the best performance in defining the origin of sediments. Misclassification was most likely due to naturally occurring high organic matter contents.



LV - Anionic Acrudox, PVA - Typic Hapludult, and OX - Typic Udifolist.

Cluster Analyses

Fig. 6.- Cluster analysis using only MS data showed poor performance. The model incorrectly identified a third group of samples (yellow). It was not capable of identifying the 8 samples with no sediment deposition either.



LV - Anionic Acrudox, PVA - Typic Hapludult, and OX - Typic Udifolist.

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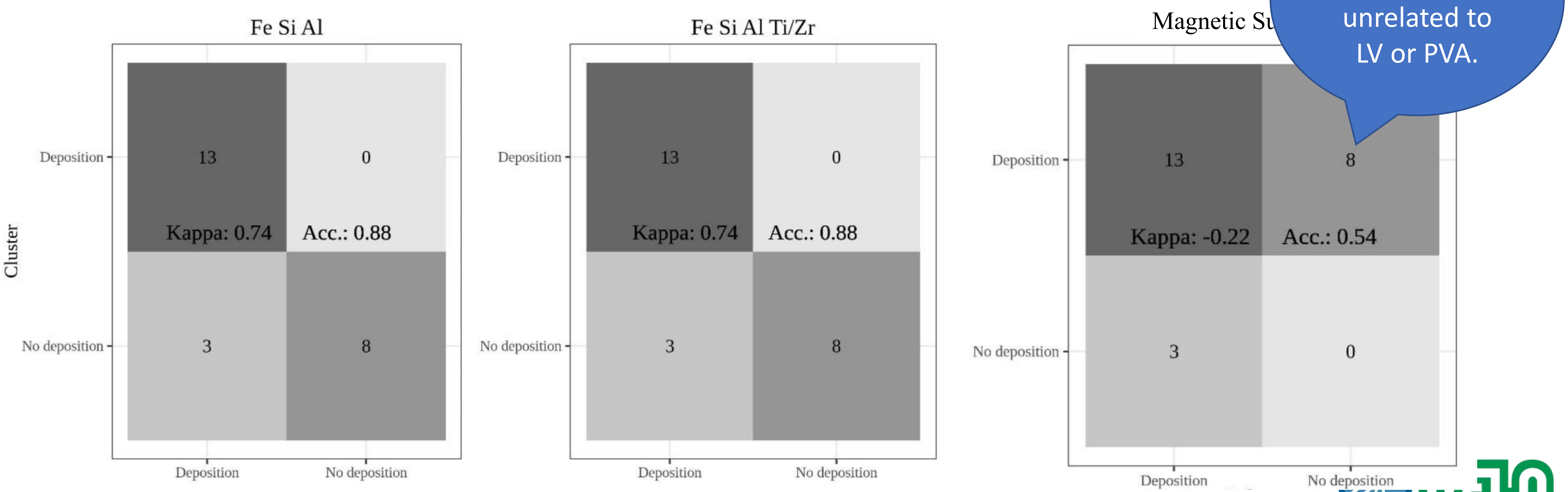
Confusion Matrix

Fig. 7.- Confusion matrices with Kappa coefficients and global accuracies (Acc) to assess the capability of cluster analyses in identifying points where sediment deposition occurred.



Conclusions

- The *fingerprinting* technique using pXRF data was able to accurately identify the source of sediment deposits in the subbasin.
- Cluster analysis of elemental contents detected by pXRF, combined with relief data, showed that the Typic Hapludult (PVA) was the main contributor to sediment deposition.
- Tracing elements Fe, Si, and Al were the most effective variables for identifying sediment sources, resulting in a global accuracy of 88% and a Kappa coefficient of 0.74.

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Scope for 2nd Experiment (Puerto Rico)

- In this study, the use of portable X-ray fluorescence spectrometer (pXRF) was used to analyze soils and sediments at two scales.
- Phase 1.- Sediment tracing in a drainage subbasin scale (Finca Alzamora, Mayagüez, PR).
- Phase 2.- Sediment tracing in small erosion plots using a rainfall simulator and Ag-Nanoparticles as a tracer.
- The hypothesis was to test whether the source of sediments can be identified using soil and sediment elemental contents obtained with pXRF and machine learning predictive models.
- The study aimed to use the *fingerprinting* technique with proximal sensors and machine learning predictive models to identify the source of sediments using soil erosion plots.

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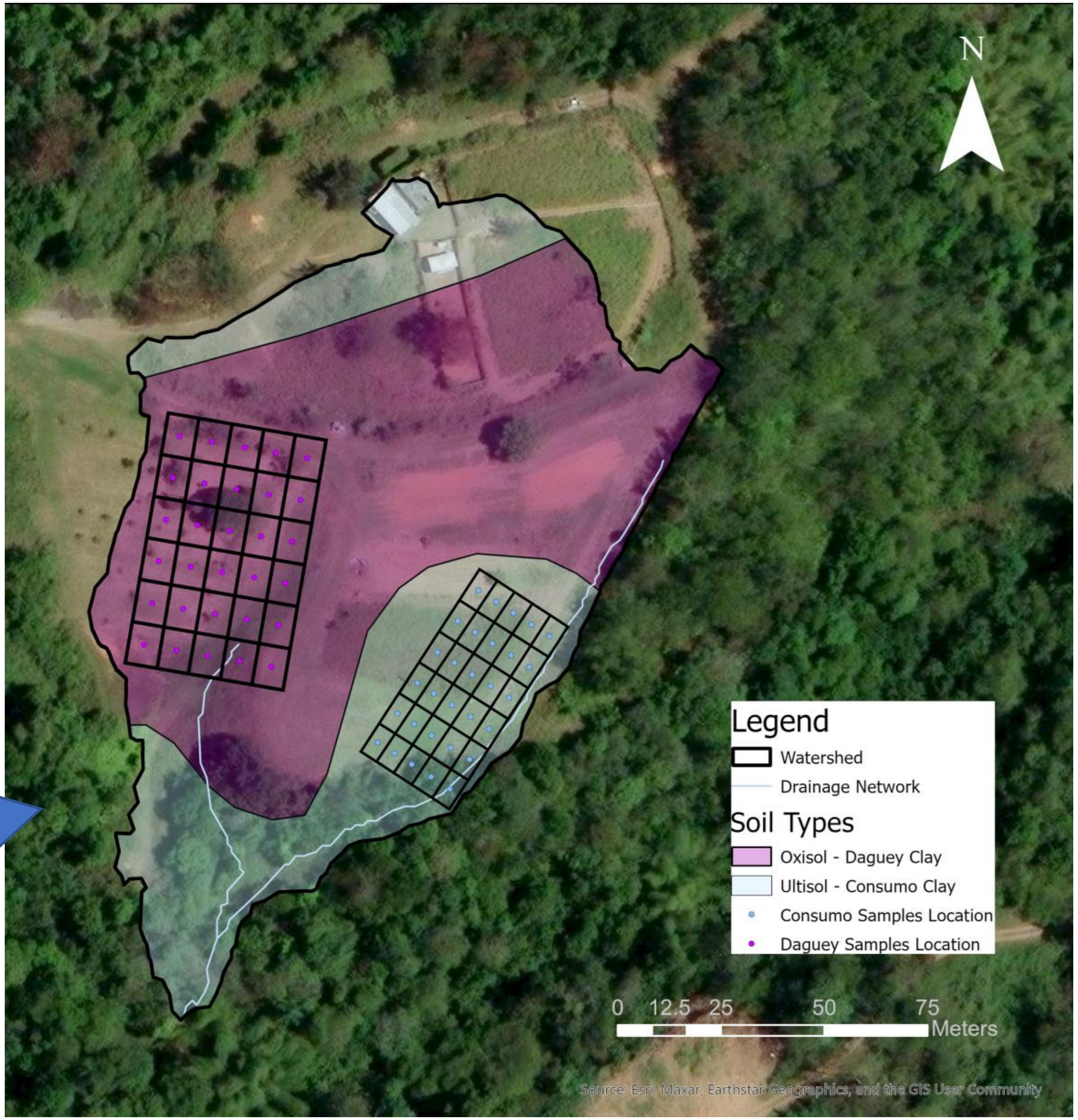
Area of Study

Fig. 8.- Drainage subbasin (1.71 ha) situated in Finca Alzamora, Mayagüez, PR. Soil classes map and drainage network.

Fig. 9.- Study area and sampling points organized by soil classes: Daguey series - Oxisol, and Consumo series – Ultisol.



60 samples were collected from the sediment contributing area.

Fig. 10.- Sampled points in the deposition area are shown.

14 samples were collected at two depths (0-5 cm, 5-10 cm).

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Soil Sampling and Lab Analyses

1. Soil samples were collected using the least of metallic tools.
2. Soil samples were air-dried and packed in polyethylene bags.
3. Soil was grinded using an agate mortar and then passed through a 250-microns sieve.
4. pXRF measurements were performed under lab conditions.

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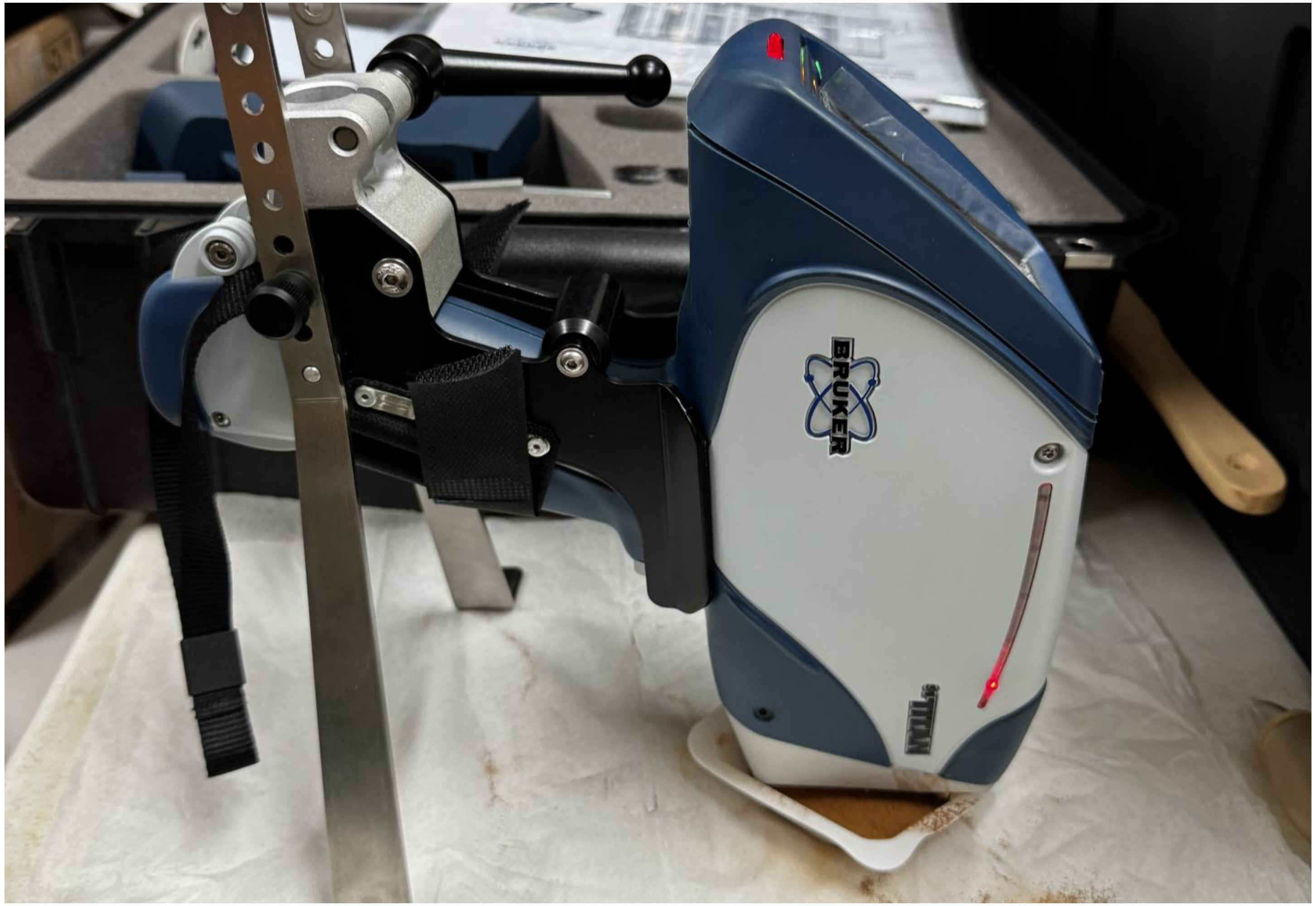
pXRF spectrometric analysis



Phase 1.- Data Processing and Statistical Analyses

- For each elemental content, Analysis of Variance (ANOVA) were performed to assess the effect of soil types.
- Random Forest-based classification method was also performed to determine the importance of the variables.
- Using ArcGIS, a layer containing the elemental concentrations of the 60 samples collected from the Daguey and Consumo areas of the subbasin was used to train the model and assess its ability to accurately identify the soil type of the samples.
- Once the model was trained, it was applied to predict the soil type of the collected samples at the closure area of the subbasin.

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Results

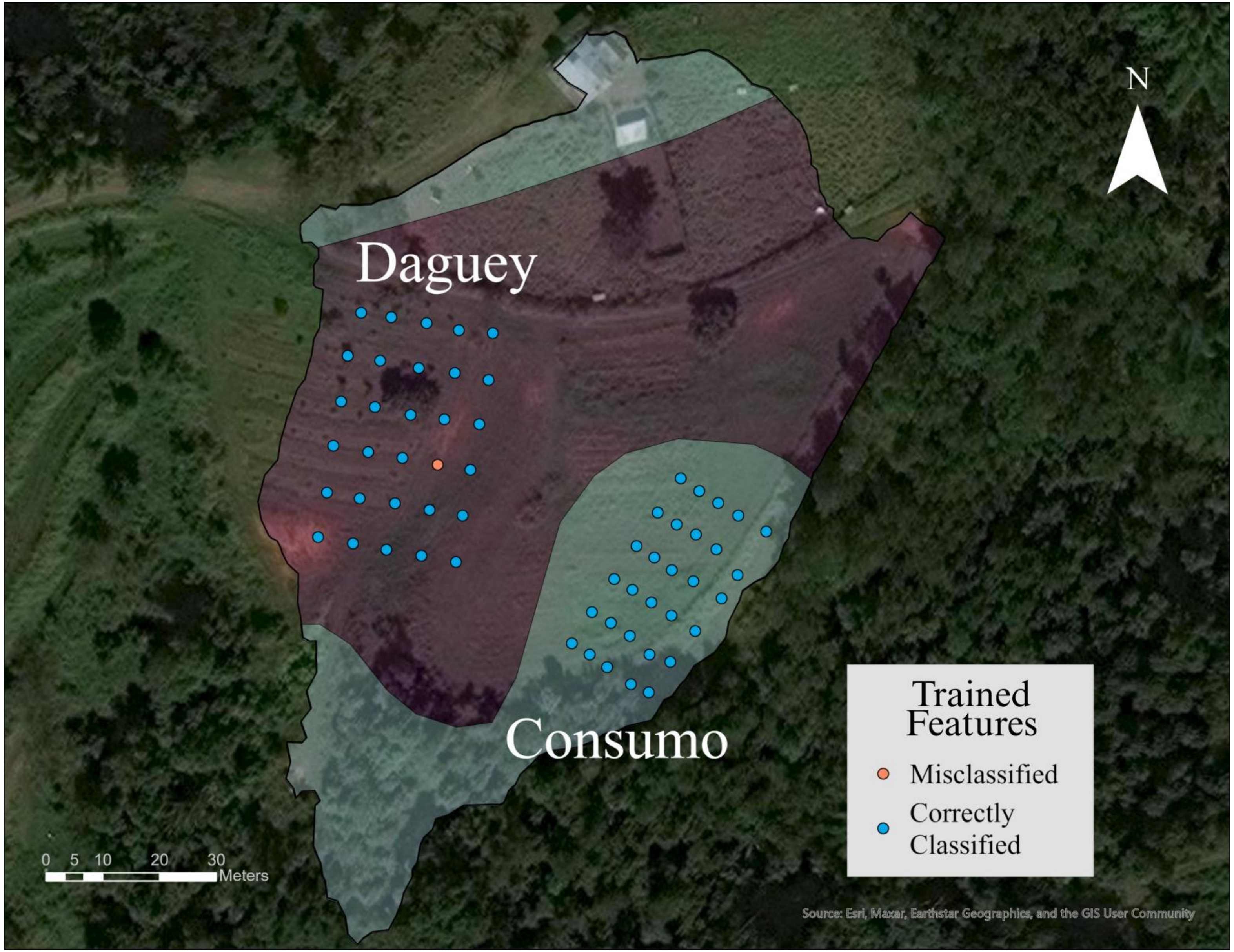
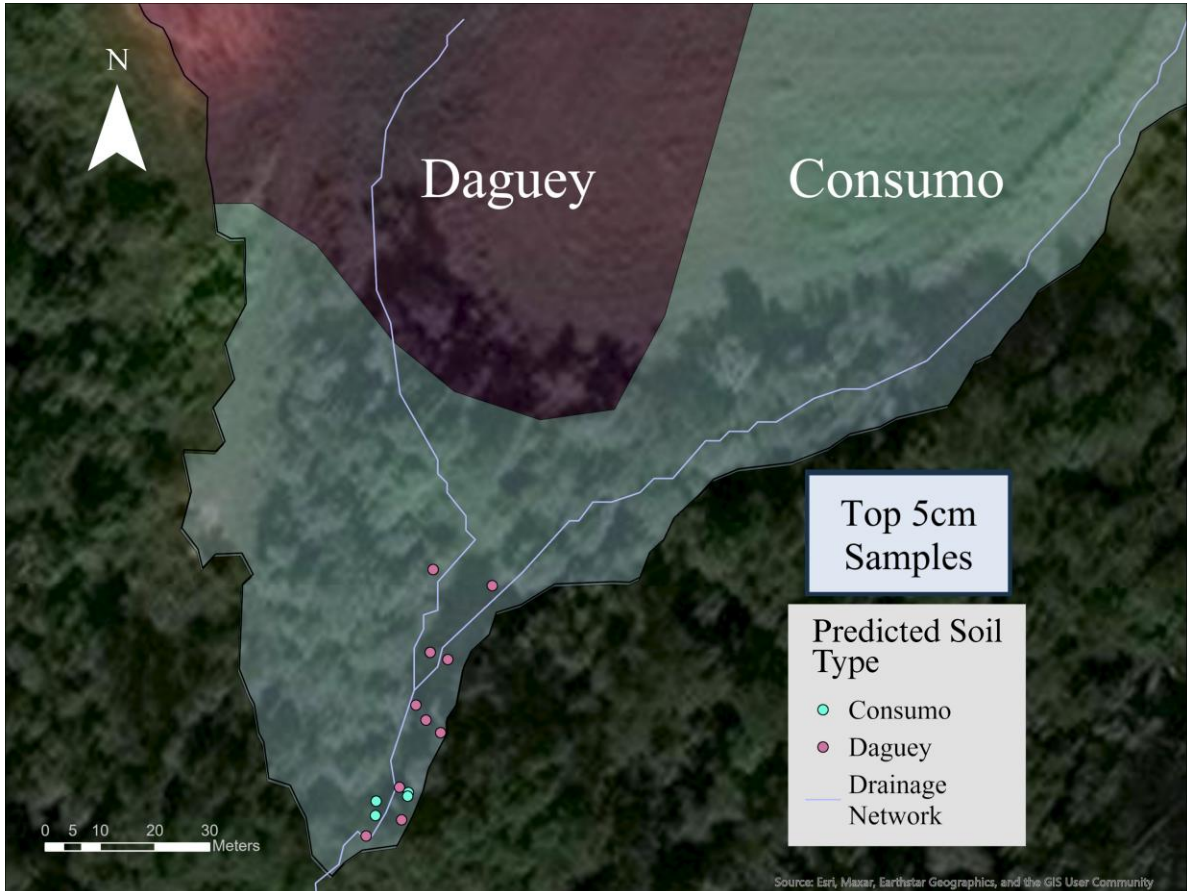
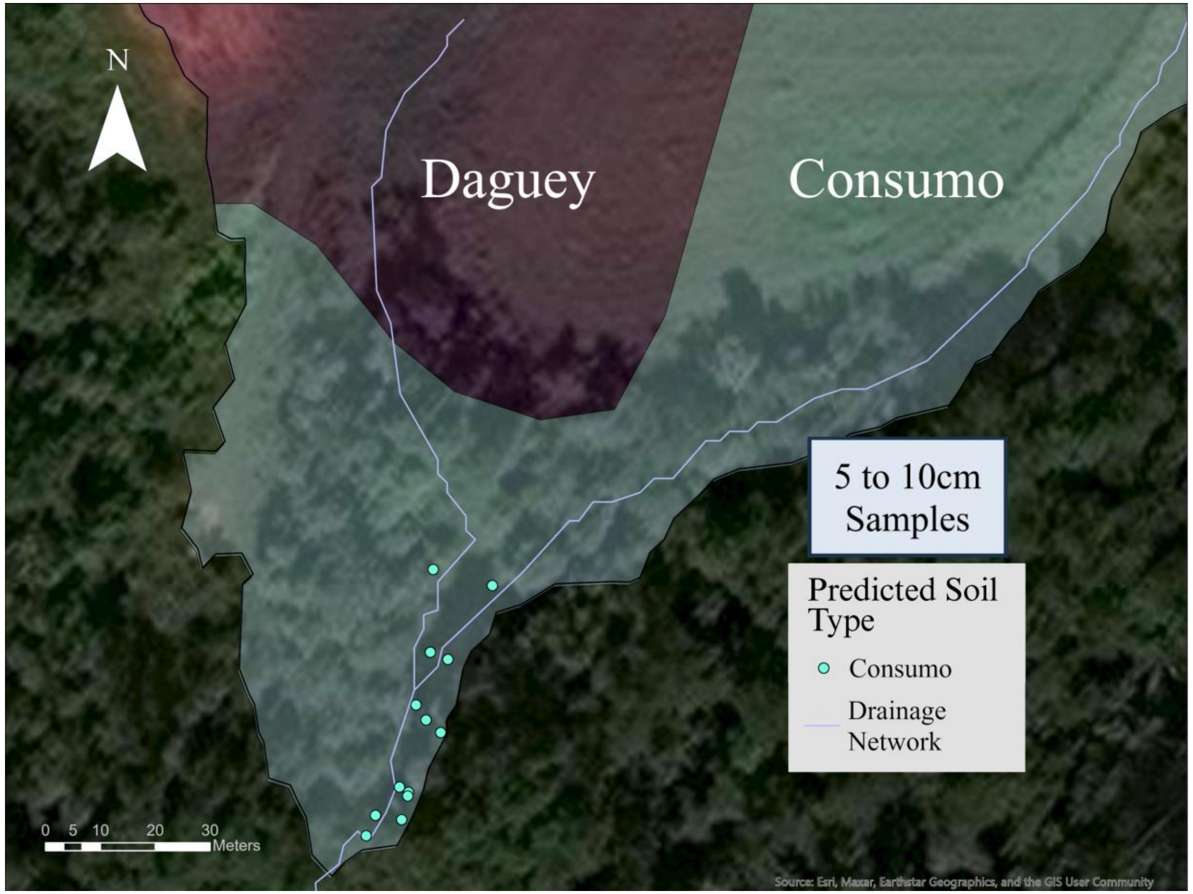


Fig. 12.- The trained model classified correctly 59 out of 60 samples.

Classification of samples in the closure area of the subbasin at Finca Alzamora.





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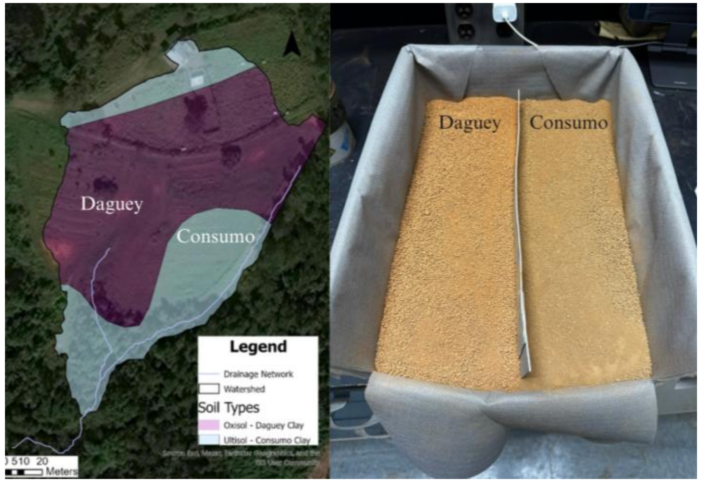
Phase 2.- Methodology

Objective	Evaluate the effect of 4 treatments (Consumo, Daguey, Daguey with Consumo, and Daguey with AgNPs and Consumo) on the elemental contents of the sediment samples collected during rainfall simulation on the erosion plots.
Design	A completely randomized design (CRD) is used, where plots are randomly assigned to treatments to ensure independence and minimize bias.
Variables	- Treatments: Consumo, Daguey, Daguey & Consumo, and Daguey with AgNPs & Consumo) - Dependent Variable: Elements contents (mg/kg) - Dependent Variable: Erosion Rate ($g/m^2 \cdot hr$) - Dependent Variable: Sediment Concentration (g/L) - Dependent Variable: Sediment Yield (g)
Treatments	- Treatment 1: Consumo soil. - Treatment 2: Daguey soil. - Treatment 3: Daguey & Consumo. - Treatment 4: Daguey tagged with AgNPs & Consumo.
Replicates	3 replicates per treatment, resulting in a total of 12 samples.
Post-Hoc Test	Tukey test was conducted to identify which groups differed significantly at $\alpha=0.05$.

Materials & Methods

Before and after saturation process



Left, the subbasin. Right, the soil setup at plot scale

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Experimental setup for the rainfall simulations

Phase 2.- Sediment Sample Procesing

- Runoff samples were collected every 5 minutes in 1-L HDPE bottles.
- Full bottles were weighed to determine the combined mass of water and sediment.
- Aprox. 0.6 mL of aluminum sulfate solution was added to each sample to induce sediment flocculation.
- After 24 hours, once the supernatant was clear and sediment had settled, the water was carefully decanted.
- Bottles were dried at 95 °C in a convenction oven and weighed again to determine sediment mass for each interval.
- Dried sediments from each bottle were combined into a composite sample for the corresponding plot. Composite samples were stored in sealed LDPE plastic bags for X-ray fluorescence (XRF) analysis.

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Phase 2.- Data Processing and Statistical Analyses

- For each elemental content, Analysis of Variance (ANOVA) were performed to assess the effect of treatments.
- The Random Forest-based predictive model was used to determine if Sediment Classification was properly performed.
- Another model was trained using the 60 samples from Phase 1, plus a composite of the Daguey Soil with AgNPs.
- A third model was trained using the 60 samples from Phase 1, plus the composite samples of the Daguey erosion plots and Consumo erosion plots.
- Confusion matrices were created to assess the accuracy of the models.

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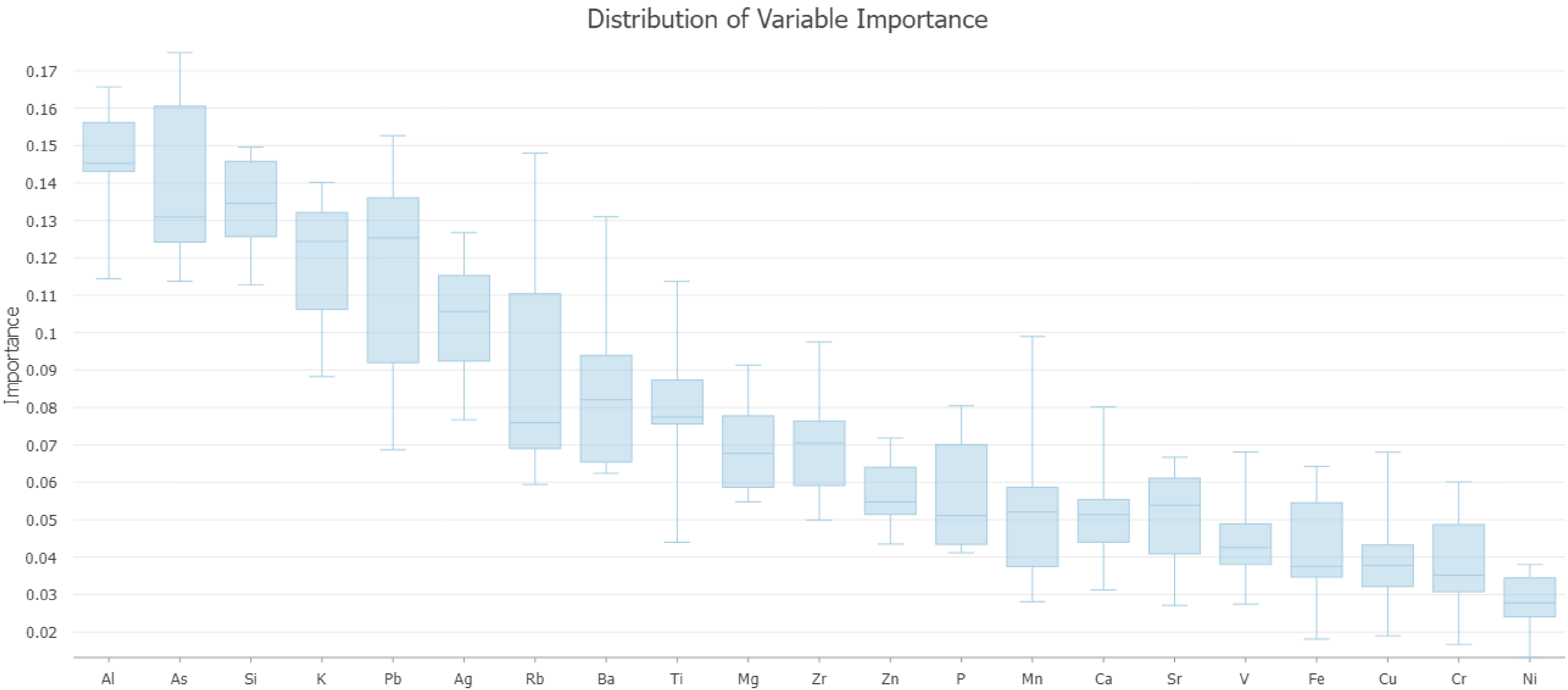
Results.- Erosion parameters

Treatment	Erosion Rate ($g\ m^{-2}\ hr^{-1}$)		Sediment Concentration ($g\ L^{-1}$)		Sediment Yield (g)		α=0.05 Significance Groups *
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	
Consumo	203.97	36.56	2.62	0.19	16.65	4.22	A
Daguey	753.97	497.34	7.99	5.13	71.74	50.01	A
Consumo & Daguey	358.03	177.51	4.23	1.78	40.26	30.48	A
Daguey AgNPs & Consumo	449.06	298.01	5.63	2.78	34.66	25.06	A

Random Forest models

	Model 1	Model 2	Model 3
Training Data	Soil Samples Phase 1	Soil Samples Phase 1 + Soil Sample of Daguey-AgNPs	Soil Samples Phase 1 + Sediment Samples of T1 and T2
Variable Importance	Al, Ag, Si, K, Mg, As	Ag, Al, Rb, Si, V, Ba	Al, As, Si, K, Pb, Ag
Accuracy (Correct Predictions)	50%	55.56%	100%

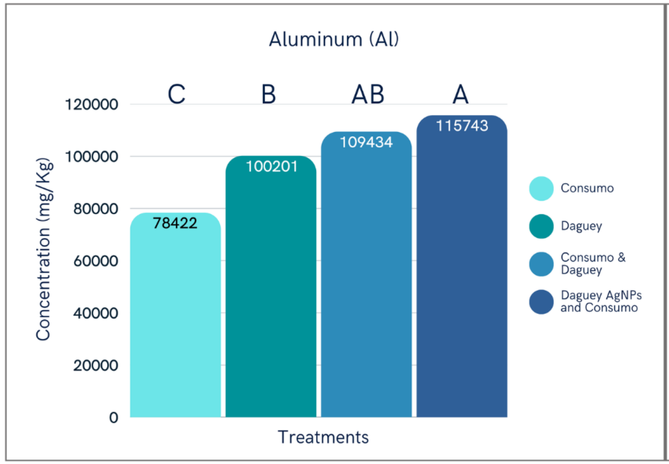
Variable Importance (Model 3)

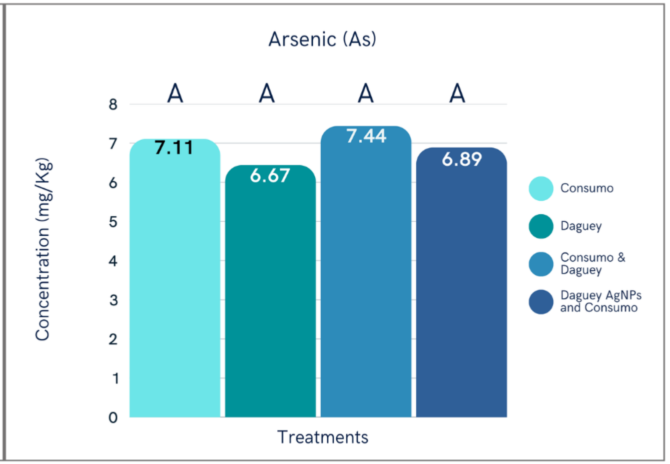


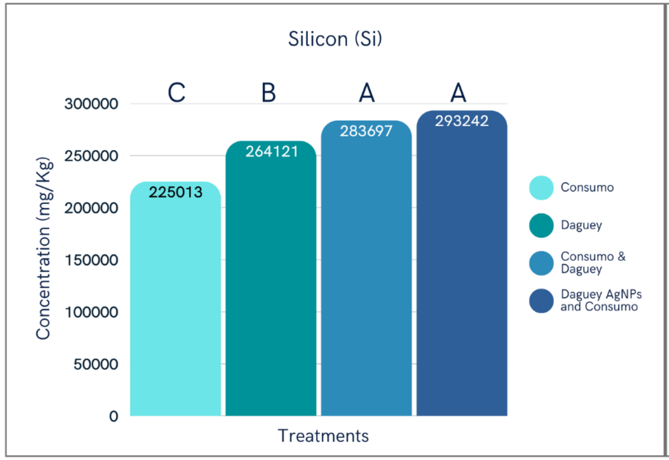
Elemental contents of high ranked variables of importance.

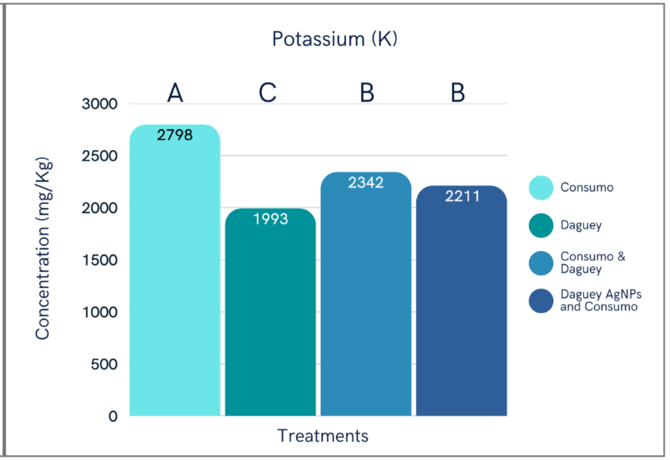
- *Different uppercase letters indicate significant differences among treatments at α=0.05.*

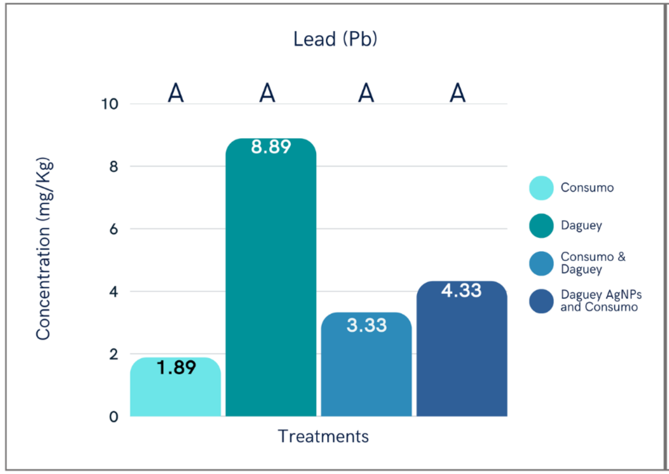
Consumo
Daguey
Consumo & Daguey
Daguey AgNPs and Consumo

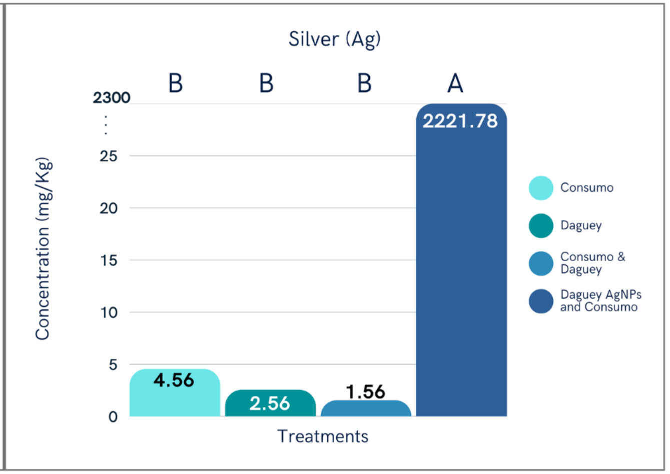












Conclusions

- The *fingerprinting* technique using pXRF data was able to classify the sediments using the phase 1 data and sediment data to create a more robust model.
- While the addition of silver nanoparticles increased the measurable silver content and confirmed its traceability with the pXRF, incorporating AgNP-tagged samples into the random forest model introduced noise and reduced classification precision to 55.6 %.
- This low-cost methodology has the potential to aid decision-making processes and identify areas that are more susceptible to environmental degradation.

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- Dr. Junior Cesar Avanzi.- UFLA Soil Science Department
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Questions?

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