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BRENNDA BEZERRA BRAGA

REUSE OF SEDIMENTS FROM SURFACE RESERVOIRS FOR AGRICULTURAL PRODUCTION IN THE BRAZILIAN SEMIARID REGION: PLANT GROWTH, SPATIO-TEMPORAL VARIABILITY, ECONOMIC ANALYSIS, REGULATORY BARRIERS AND MAPPING OF ITS ATTRIBUTES BY REMOTE SENSING

FORTALEZA
2024

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Orientador: Prof. Dr. Pedro Henrique Augusto Medeiros.
Coorientador estágio sanduíche: Dra. Saskia Foerster.

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Aprovada em: ___/___/______.

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ABSTRACT

This study explored the potential of sediment reuse from surface reservoirs located in the Brazilian semiarid region as a soil conditioner for agricultural production, to reduce the demand for high-consumption chemical fertilizers through sediment replacement. The thesis is divided into three chapters organized in the format of scientific papers. The first chapter (I) evaluates: the heterogeneity of sediments physicochemical properties at regional scale and the effect of the substrate containing sediment on the growth and physiology of maize. In general, the results showed that reservoirs sediments in semiarid regions have higher nutrient contents compared to soil. Sediments increased the leaves' chlorophyll content, photosynthesis rate and growth in relation to the control treatment containing only soil. Additionally, there weren’t significant differences between the biomass production and plants' nutrients extraction with the largest dose of the most enriched sediment when compared to the treatment with chemical fertilizer. In the chapter two (II) the sediment variability, the economic and environmental benefits and regulatory barriers for applying the practice were analyzed. We also conducted a cost-benefit analysis of reservoir sediment reuse, in face of the latest global economic crisis. The analysis of the reservoirs’ volume dynamics showed that the sediment has been exposed frequently and for long time periods, enabling its excavation. Spatio-temporal variability of the physical-chemical characteristics of the sediment may be an obstacle to extending the practice. Chapter three focused on mapping physicochemical properties of soils and reservoirs sediments from the Brazilian semiarid region by multi- and hyperspectral data. We concluded that the combination of reflectance spectroscopy with multivariate statistical techniques seems to be an effective approach for predicting electrical conductivity, organic carbon and clay content of soils and reservoir sediments in semi-arid regions.

Keywords: sustainable agriculture; deposited soil reuse; nutrients cycling; soil spectroscopy; spectral indices; multivariate statistical.

RESUMO

Este estudo explorou o potencial de reutilização de sedimentos de reservatórios superficiais localizados no semiárido brasileiro como condicionador de solo para a produção agrícola, a fim de reduzir a demanda por fertilizantes químicos por meio da substituição por sedimentos de reservatórios. A tese está dividida em três capítulos organizados no formato de artigos científicos. O primeiro capítulo (I) avalia: a heterogeneidade das propriedades físico-químicas dos sedimentos em escala regional e o efeito do substrato contendo sedimentos sobre o crescimento e a fisiologia do milho. Em geral, os resultados mostraram que os sedimentos dos reservatórios de regiões semiáridas têm maior teor de nutrientes em comparação com o solo. Os sedimentos aumentaram o teor de clorofila das folhas, a taxa de fotossíntese, o crescimento e a produção de biomassa, em comparação ao tratamento de controle contendo apenas solo. Além disso, não houve diferenças significativas entre a produção de biomassa e a extração de nutrientes das plantas com a maior dose do sedimento mais rico em nutrientes em comparação com o tratamento com fertilizante químico. No capítulo dois (II), foram analisados a variabilidade do sedimento, os benefícios econômicos e ambientais e as barreiras regulatórias para a aplicação da prática em escala real. Também realizamos uma análise de custo-benefício da reutilização de sedimentos de reservatórios, em face das últimas crises econômicas globais. A análise da dinâmica do volume dos reservatórios mostrou que o sedimento tem sido exposto com frequência e por longos períodos de tempo, permitindo sua escavação. A variabilidade espaço-temporal das características físico-químicas do sedimento pode ser um obstáculo à ampliação da prática. O capítulo três concentrou-se no mapeamento das propriedades físico-químicas de solos e sedimentos de reservatórios da região semiárida brasileira por meio de dados multi e hiperespectrais. Concluímos que a combinação de espectroscopia de refletância com técnicas estatísticas multivariadas parece ser uma abordagem eficaz para prever a condutividade elétrica, o carbono orgânico e o teor de argila de solos e sedimentos de reservatórios em regiões semiáridas.

Palavras-chave: agricultura sustentável; reutilização de solo depositado; ciclagem de nutrientes; espectroscopia de solo; índices espectrais; estatística multivariada.

SUMMARY

1 INTRODUCTION

Due to the high rainfall variability in the Brazilian semi-arid region and the occurrence of long periods without rain, society has adopted techniques to cope with drought, with focus on the construction of surface reservoirs. However, silting is causing a decrease in the water storage capacity of those structures, reducing their depth, increasing water losses by evaporation and contributing to the degradation of water quality by adsorbed pollutants. In a context where mitigating solutions are necessary, removal of the nutrient-enriched sediment from the reservoirs' beds and their subsequent reuse for soil fertilization have been proposed.

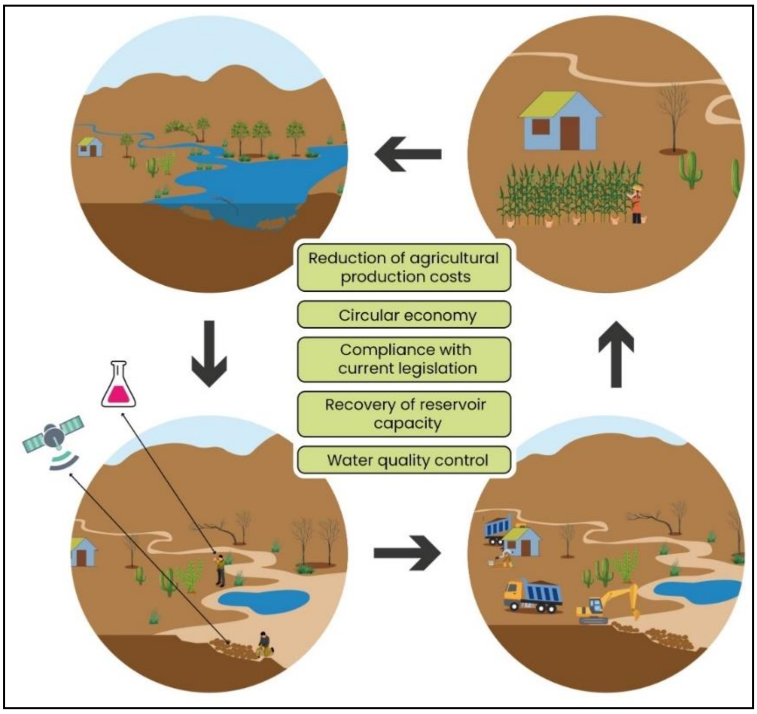
The study was based on the following fundamental questions: To what extent can the reuse of sediment from surface reservoirs in the Brazilian semiarid region, as a soil conditioner for agricultural production, address the demand for high-consumption chemical fertilizers, considering sediment variability, economic, agricultural and environmental benefits, and regulatory barriers? How does the spatio-temporal variability of the sediment's physical-chemical characteristics impact the feasibility and safety of extending sediment reuse practices, and what are the potential implications for crop yields, environmental well-being, and societal benefits? How can the electrical conductivity, clay content and organic carbon of the bottom sediment of small reservoirs in the Banabuiu river basin be mapped to identify potential reservoirs for the application of the sediment reuse technique?

This PhD dissertation is divided into three chapters organized in the format of scientific papers. Chapter I assesses the heterogeneity of physicochemical properties in sediments at a regional scale and examines the impact of substrate containing sediment on maize growth and physiology. The findings reveal that sediment from reservoirs in semiarid regions generally has higher nutrient content compared to soil. Sediments enhance chlorophyll content, photosynthesis rate, and overall growth when compared to the control treatment with only soil. Moreover, there were no significant differences in biomass production and nutrient extraction between the highest dose of enriched sediment and the treatment with chemical fertilizer. This chapter has been published in a scientific journal of relevant impact and is available at the following link: https://link.springer.com/article/10.1007/s11368-023-03679-5.

In Chapter II, we delve into sediment variability, economic and environmental benefits, and regulatory barriers for implementing sediment reuse. A cost-benefit analysis is conducted in light of the recent global economic crisis. The analysis of reservoir volume dynamics indicates frequent and prolonged exposure of sediment, facilitating excavation. However, spatio-temporal variability in the physical-chemical characteristics of sediment may pose challenges to expanding the practice. Therefore, it is relevant to map the spatial distribution of the sediment characteristics. Recently, we demonstrated that diffuse reflectance spectroscopy might be useful to characterize sediments at lower costs and efforts than by laboratory analyses: for instance, regression models for electrical conductivity and clay content performed in the range of good to very good in the study region. A further promising approach is the application of spaceborne imaging spectroscopy (Chapter III) to estimate the concentration of elements such as sodium, the electrical conductivity, the content of clay and organic matter in the sediment. The derived information can be used for informed decisions in the application of sediment reuse practice. For example, if the electrical conductivity of the sediment is higher than 4 dS/m, addition of sediment to the soil may prevent plant growth and, therefore, its reuse is not recommended. The last two chapters are in the process of being published, but Chapter II is available as preprint at the following website: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4661553.

Thereby, sediment reuse can also potentially promote de-silting of reservoirs, reducing the carbon footprint associated with traditional fertilization and improving the water quality of small reservoirs, the main source of water supply for rural families, by removing nutrients that could return to the water column. In addition, the use of sediments may represent an alternative to increase agricultural production, being less susceptible to market price variation than commercial fertilizers.

Figure 01 - An overview of the sediment reuse practice.



2 CHAPTER I: REUSE OF SEDIMENT AS SOIL CONDITIONER IN A SEMIARID REGION DOMINATED BY SUBSISTENCE FARMING: SEDIMENT CHARACTERIZATION AT REGIONAL SCALE AND EFFECT ON MAIZE CROP

Abstract: The increasing demand for fertilizers and their rising prices has led to the search for new nutrient sources, especially in rural areas where family farming predominates. In this study we assessed the potential of reusing sediment silted in surface reservoirs as soil conditioner in a semiarid region, focusing on two features: the characterization of sediment physicochemical properties at regional scale; and the effect of the substrate containing sediment on the growth and physiology of maize. Sediment from the beds of 14 reservoirs were investigated and two of them were used for preparation of substrate for maize cultivation. Differences between the sediments' physicochemical properties were analyzed using ANOVA and Tukey's test at a significance level of 0.05. The experimental design of the plant experiment was entirely randomized, in a factorial arrangement of two sources and four doses of sediment: 25, 50, 75, and 100% of the economic dose of 100 T hectare^{-1} previously proposed in the study region. Two treatments were considered as controls: a substrate containing only soil and a treatment containing soil and chemical fertilizer. The data for each treatment were submitted independently considering the doses and sediment sources, and the means were compared by Tukey's test. In general, nutrient contents were higher in the sediment of the surface reservoirs than in the soil. For instance, the concentrations of nitrogen and potassium were three to ten times higher in the sediment (compared to soil) and the organic matter content was up to six times higher. In the plant growth experiment, sediments' dose and source influenced all the analyzed variables. Addition of sediments to the soil increased the leaves' chlorophyll content, photosynthesis rate and growth in relation to the treatment containing only soil. There were not significant differences between the biomass production and plants' nutrients extraction with the largest dose of the most enriched sediment when compared to the treatment with chemical fertilizer. The experiment of maize plant growth showed the feasibility of using sediment silted in reservoirs as soil conditioner due to the enrichment of nutrients, organic matter and fine particles. Therefore, sediment reuse has potential to improve livelihoods and food security, as well as contributing to a circular economy. However, prior analysis is required to avoid soil contamination and to set the most appropriate sediment dose, due to the high spatial variability of the sediment characteristics.

Keywords: sediment reuse, nutrient recycling, biomass production, agricultural utilization, sustainable ecosystem

2.1 Introduction

The Brazilian semiarid region is one of the most densely populated dry areas in the world, with approximately 27 million people (12% of the Brazilian population) in an area of 1.03 million km². In this area is located the Banabuiu basin, where almost 60% of the population (more than 210,000 habitants) lives in rural areas (COGERH 2009). The small-scale family farming predominates in the region, with a focus on maize (Magalhães et al. 2021), beans, and sheep farming (Pereira et al. 2019). However, in the global outlook of increasing demand for fertilizers (FAO 2015) and rising prices of chemical inputs (Hassen and Bilali 2022), the use of new nutrient sources, such as sediments from the bed of surface reservoirs, is an alternative strategy (Livsey et al. 2021). Indeed, according to Braga et al. (2019), the reuse of sediment as a nutrient source in agricultural production would already generate savings of 29% when compared to conventional fertilization. The reuse of sediments can also correct soil physicochemical deficiencies, favoring the growth and productivity of crops, such as maize, sunflower (Braga et al. 2017), lettuce (Canet et al. 2003), ryegrass (Kiani et al. 2020) and photinia (Mattei et al. 2017).

Due to the high climatic variability in the Brazilian semiarid region, mainly due to long periods without precipitation, a dense network of surface reservoirs has been developed (approximately one reservoir per 7 km², de Araújo and Medeiros, 2013). However, the sediment accumulation in water bodies, makes the reservoirs shallower, decreasing the capacity to store water by almost 2% per decade in Brazilian semiarid regions (de Araújo et al. 2006) and increasing water losses by evaporation (Rodrigues et al. 2021). Additionally, sediment can carry pollutants into the lakes, contributing to water quality degradation (Davey et al. 2020; Lira et al. 2020), a socio-hydrologic phenomenon referred to as “water quality effect” (Medeiros and Sivapalan, 2020), which has been observed across the planet. According to Vörösmarty et al. (2003), more than 50% of the eroded soil mass that can be transported in regulated basins is retained in surface reservoirs. Also, according to Wisser et al. (2013), the negative effects of siltation on reservoir water quality is of greater concern in regions with high rates of seasonal flow variation and population growth.

Therefore, the removal of sediment from a reservoir’s bed for reuse can partially recover the reservoir’s storage capacity which has been lost by siltation, as well as contribute to maintain the water quality at acceptable levels (Leue and Lang, 2012; Mattei et al. 2017; Renella 2021). In the study area, sediment removal could be performed by backhoe loaders, generating lower costs than dredging, since the smaller reservoirs in the region dry up regularly, usually every two years. However, the sediments must be characterized physicochemically and biologically before being applied to the soil, because they can accumulate harmful constituents such as heavy metals (Fonseca et al. 2003) and/or salts (Braga et al. 2019), preventing their indiscriminate use in agriculture.

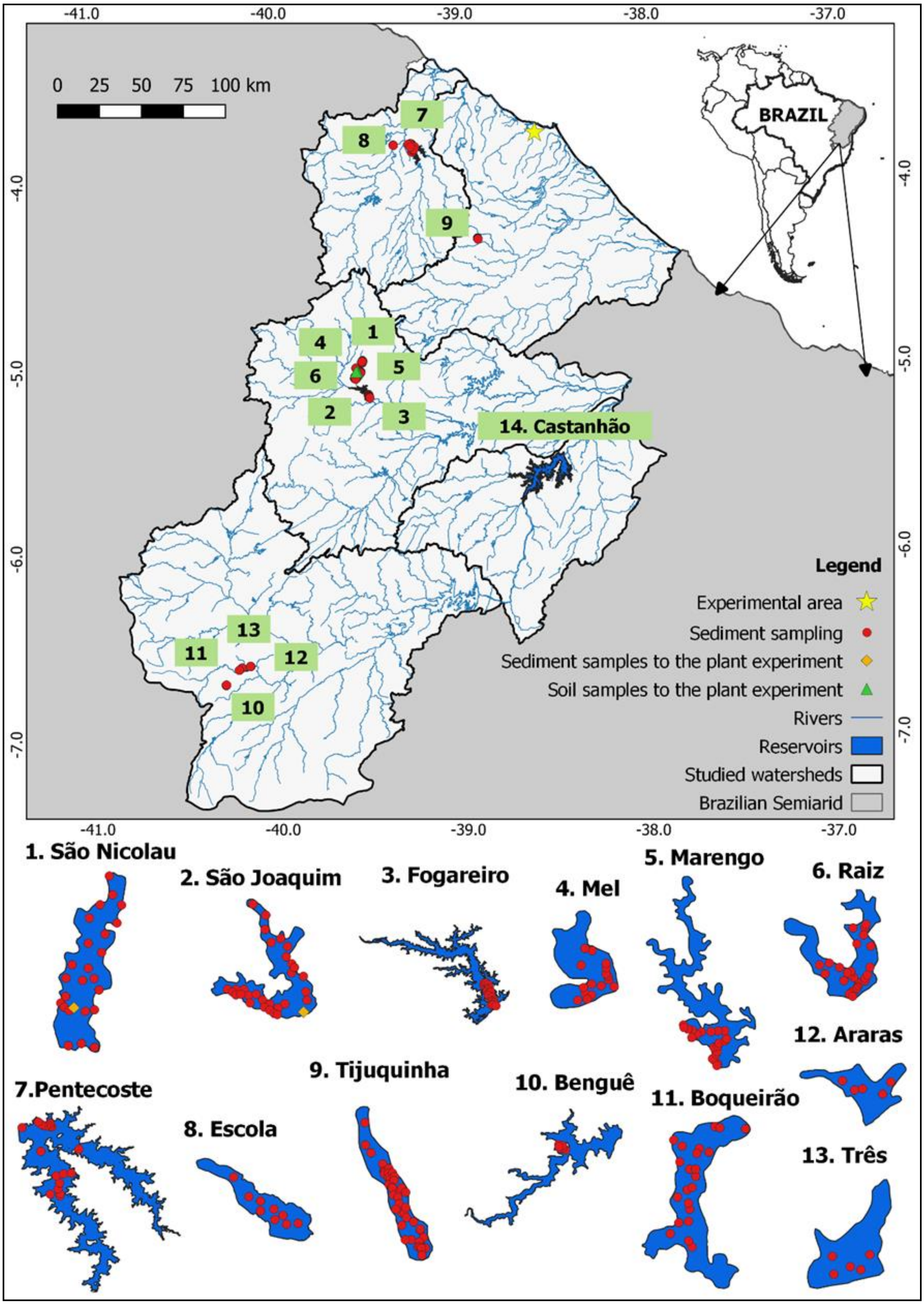
The reuse or recycling of sediment can also be intended in other types of applications. For instance, in the field of soil recovery, Capra et al. (2015) observed positive results in the physicochemical properties of soils degraded by surface erosion when sediment was added. Some of the beneficial effects were an increase in nutrient content, such as N and K, and an increase in total organic carbon and cation exchange capacity, recovering the agronomic efficiency of these soils. Another evidence of the beneficial effects of sediment reuse for recovery of eroded soils was shown in the work of Bondi et al. (2016), in which sediment from different lakes was used and demonstrated to improve soil fertility by increasing the carbon in humic substances. Sediment could support ecosystem restoration in Canada's prairie region, since according to Martens (2022), approaches that support healthy ecosystem functioning and that are able to maximize yields from annual monocultures need to be prioritized. Brils et al. (2014) report on the potential for sediment reuse in stabilizing and protecting coastal areas from flooding in the Netherlands. The authors argue that sediment can be considered as a resource (rather than waste) when inserted, through the practice of reuse, within the circular economy philosophy.Therefore, sediments deposited in surface reservoirs represent a material of great potential utility, either in the recovery of soil layers lost by erosion processes or functioning as sources of nutrients for plants. The aim of this study was to evaluate the heterogeneity of physicochemical properties of sediments from the bed of surface reservoirs in the Brazilian semiarid tropical region and then investigate the addition of sediments from two of those reservoirs to soils, assessing its effects on the growth, leaf gas exchange and nutrient extraction of maize (*Zea Mays* L.).

2.2 Material and methods

2.2.1 Spatial variability of sediment characteristics

In this study, we produced a database of sediments sampled from 14 reservoirs of five different basins in the Brazilian semiarid region (Fig. 1) using data from previous works performed by us (COGERH, 2016; Brosinsky et al., 2017; Braga et al., 2017; Lira et al., 2020; Carvalho et al., 2022) and sediment characterization within this study. In the study region, annual precipitation is of the order of 800 mm, average annual temperatures range from 23 to 27 °C, mean potential evaporation of over 2,000 mm per year, and average relative humidity of air around 50%. This region is also characterized by strong insolation and rainfall regime marked by irregularity and concentration of precipitation in a short period (mainly from February to May). According to Jacomine (1996), the region's geology can be divided into three areas: crystalline, areas covered by more or less sandy materials and sedimentary areas. The relief is very variable and the average altitude ranges from to 400 and 500 m. The region mostly presents Latosol, Litholic Neosols, Argisols and Luvisols, classified as soils with low productive potential, either due to fertility and profile depth limitations, or due to drainage limitations and high levels of sodium (Silva et al. 2010).

Figure 1 - Location of the study region and sediment sampling points.



The sediment sampling conducted in this study was preceded by the cleaning of the surface for litter removal. The material was then collected from the top layer up to 20 cm depth, dried completely at 60 °C, sieved to 2 mm and then sent to physicochemical laboratory analyses. It is important to note that the study region faced a severe drought between 2012-2017, when most of the samplings were performed (Table 1), most reservoirs (mainly small reservoirs) fell dry. Additionally, we compared sediments to soil's properties obtained from the database containing around 800 samples provided by the Meteorology and Water Resources Foundation of Ceará (FUNCEME). Although this study focuses on a regional scale, it is still the most comprehensive soil database encompassing the study area.

Table 1 - Database of sediment from superficial reservoirs located in the Brazilian semiarid region.

Reference	Basin	Reservoir	RC	CS	NS	YS	EE
Bronsinsky et al. (2017)	Banabuiú	Mel	0.06	3.02	17	2014	pH, N, Ca, Mg, O.M, Zn, Al, E.C, K, C, P, Fe, Mn, Cu, granulometry
		Raiz	1.5	5.3	28		
Braga et al. (2017) **Lira et al. (2020)**	Fortaleza Metropolitan Region	Tijuquinha	0.5	45.4	*	2015	N, O.M
COGERH (2016)	Mid Jaguaribe	Castanhão	6,700	45,309	4	2016	N, O.M
Carvalho et al. (2022)	Upper Jaguaribe	Três	0.01	0.51	5	2016	pH, N, Ca, Mg, O.M, Zn, Al, E.C, K, C, P, granulometry
		Araras	0.01	0.48	5		
		Benguê	19.6	931	6		
		Boqueirão	0.05	12	26		
	Curu	Escola	0.05	2.8	10		
		Pentecoste	360	3,254	20		
	Banabuiu	Fogareiro	118	5,105	20		
		Marengo	15.3	120	20		
		São Joaquim	5	30.8	20		
		São Nicolau	0.9	36.1	20		
This study	Banabuiu	São Joaquim	5	30.8	22	2021	pH, N, Ca, Mg, O.M, Zn, Al, E.C, K, C, P, granulometry
		São Nicolau	0.9	36.1	21		

Legend: RC – Reservoir capacity (hm³); CS – catchment size (km²); NS – numbers of samples; YS – year of sampling; EE – elements evaluated; *6 samples to N and 46 to O.M;

The analysis of sediment's physicochemical characteristics was carried out at the Laboratory of Soil and Water of the Federal University of Ceará (UFC). The following attributes were examined (Table 1): pH, electrical conductivity (EC), granulometry, soil macro and micronutrients - nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) - aluminum (Al), carbon (C) and organic matter (OM). The analyses were conducted as recommended in the Manual of Soil Analysis Methods of the Brazilian Agricultural Research Corporation (EMBRAPA, 2017) and some of them are follow described: N soil content was performed using the Kjeldahl method, in which N is converted to ammonium sulphate through oxidation, and the released ammonia is determined by acidimetry; the P phosphorus by molecular absorption spectrophotometry; K content after its extraction with dilute hydrochloric acid solution and subsequent determination of the exchangeable potassium by flame spectrophotometry; C by an oxidation of organic matter via a wet process with potassium dichromate in a sulfuric medium. The excess dichromate after oxidation is titrated with a standard solution of ferrous ammonium sulphate; EC and pH after a preparation of a saturation paste by addition of water to the sediment sample until saturation, and direct reading with a conductivity and ph meter, respectively; and the granulometry was performed using the pipette method, with agitation and suspension of the silt and clay fractions in dispersing solution, and quantification of the suspended fraction after sedimentation. When carrying out quality control measures and evaluating uncertainties, the laboratory performs three separate analyses and observes variations of less than 2%. Any differences of up to 5% are considered acceptable and trigger a re-analysis if they exceed this limit. Differences between mean values of sediments' physicochemical properties were analyzed using two-way ANOVA (for the different basins and reservoirs) and Tukey's test at a significance level of 0.05. For further details, consult the relative studies of each project, provided in Table 1.

2.2.2 Reuse of sediment for maize cultivation

2.2.2.1 Sediment sampling and experiment conduction

The sediment used as soil conditioner to maize cultivation was sampled from two of the studied reservoirs (São Nicolau and São Joaquim) in January 2021, a period in which they were partially empty. The São Nicolau (SN) and São Joaquim (SJ) reservoirs present storage capacities of approximately 890,000 m^3 and 5,100,000 m^3, whose catchments drain areas of approximately 36 km^2 and 31 km^2, respectively. The soil used in the experiment was collected in the same period from the region where the reservoirs are located. Soil samples were collected at three points at a distance of 500 m from each other and, on average, 7 km from the SN and SJ reservoirs. The geographic location of the study area, including the soil and sediment sampling points, is presented in Fig 1.

The physical and chemical analyses of the soil and sediment samples were performed according to the methods recommended by the Brazilian Agricultural Research Corporation (EMBRAPA, 2017). The results are presented in Table 2.

Table 2 - Physical-chemical analysis of soil and sediment used in the composition of substrates for maize plant growth

	pH	*EC*	*OM*	*N*	*P*	*Cu*	*Ca*	*Mg*	*Na*	*K*	C/N	*Sand*	*Silt*	*Clay*
		$dS.m^{-1}$	*$g.kg^{-1}$*		*$mg.kg^{-1}$*			*$cmol.kg^{-1}$*					*%*	
S	6.6	0.5	8.5	0.5	6	2.6	2	0.4	0.1	0.2	10	87	10	3
SJ	7.4	0.9	5.5	0.6	16	1.3	3.8	0.7	0.3	0.3	10	75	21	4
SN	7.2	0.8	15.4	0.9	219	1.9	8.7	3.5	0.8	0.3	9	69	22	9

Legend – S: Soil, SN: São Nicolau’s sediment, SJ: São Joaquim’s sediment, EC: electrical conductivity of saturated soil extracts, OM: organic matter, N: nitrogen, P: phosphorus available, Cu: copper, Ca: calcium, Mg: magnesium, Na: sodium, K: potassium, C: carbon.

The experiment was conducted from August to November 2021 in a greenhouse located in Fortaleza (3°44'45.3"S; 38°34'56.1"W), Ceará – Brazil, at an approximate distance of 200 km from the reservoirs where the sediments were collected. During the months of the experiment, relative humidity inside the greenhouse ranged between 30 and 72%, with an average of 52%, and the average temperature was 35.7 ºC, ranging from 29.1 to 43.9 ºC.

The experimental design (Table 3) of the study was entirely randomized, in a factorial arrangement of two types of sediment (obtained from the São Nicolau and São Joaquim reservoirs) and four sediment doses (0.6, 1.2, 1.8 and 2.4 kg pot^{-1}), corresponding to 25, 50, 75, and 100% of the dose recommended by Braga et al. (2019) based on an economic feasibility analysis (100 t ha^{-1}), which we adopted as a reference value to assess how sediment source and dose could affect the plant performance. The sediment mass applied per pot in the reference treatment (2.4 kg pot^{-1}) was obtained by dividing the dose of 100 t ha^{-1} (Braga et al. 2019) by the recommended crop density of 41,667 plants per hectare (EMBRAPA, 2002). The economic feasibility study indicated the limit mass of sediment that could generate costs equal to or lower than those obtained if mineral fertilizers had been used. Furthermore, two treatments were applied as controls: substrate containing only soil from the region and a treatment containing soil and chemical fertilizer at 100% of the nutritional recommendation (NR) for maize, according to Coelho (2008).

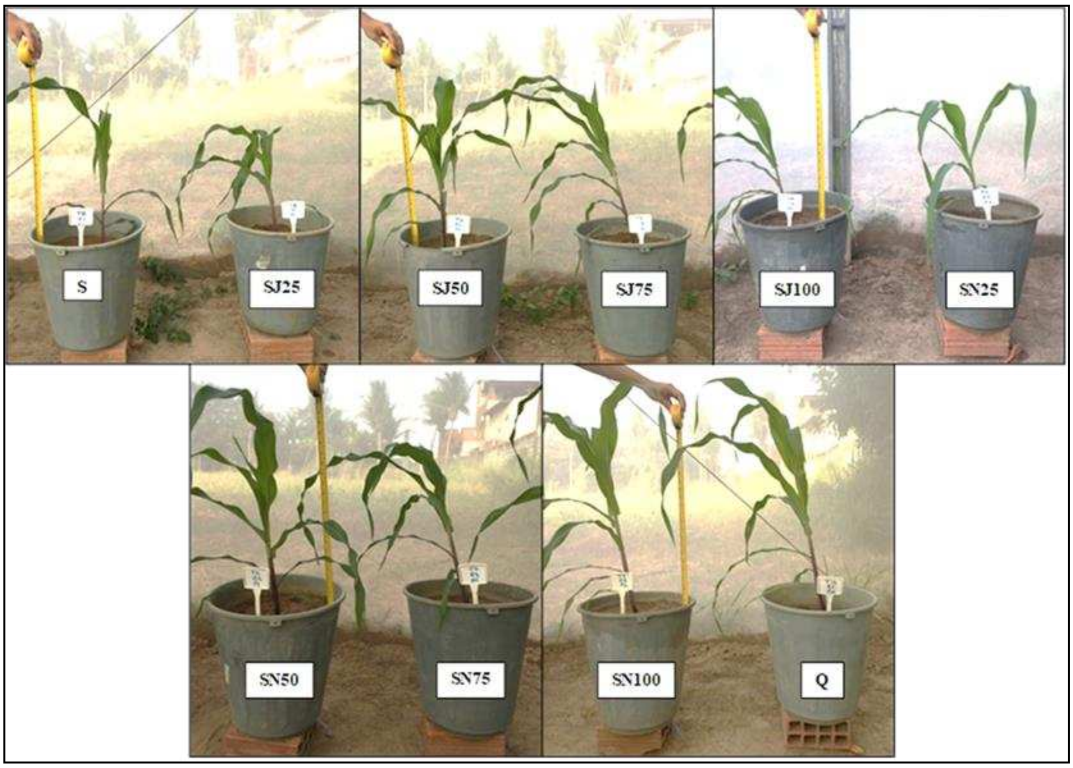
Table 3 - Experimental design, mass of sediment or fertilizer added, and corresponding amount of nutrients.

Treatment	***Chemical Fertilizer***	***São Joaquim's sediments***	***São Nicolau's sediment***	***N***	***P***	***K***	***Ca***	***Mg***
	(g.pot^{-1})	***(kg.pot^{-1})***		***(g.pot^{-1})***				
S	0	0	0	13.26	0.16	2.43	10.40	1.20
SJ25	0	0.6	0	13.64	0.17	2.49	10.86	1.25
SJ50	0	1.2	0	14.02	0.18	2.55	11.31	1.30
SJ75	0	1.8	0	14.39	0.19	2.61	11.77	1.35
SJ100	0	2.4	0	14.77	0.20	2.67	12.22	1.40
SN25	0	0	0.6	13.83	0.29	2.50	11.44	1.45
SN50	0	0	1.2	14.40	0.42	2.57	12.49	1.70
SN75	0	0	1.8	14.97	0.55	2.64	13.53	1.95
SN100	0	0	2.4	15.54	0.68	2.71	14.57	2.20
Q	NR	0	0	16.02	0.52	4.09	10.40	1.20

Legend - SN: São Nicolau's sediment, SJ: São Joaquim's sediment; the numbers 100, 75, 50 and 25 correspond to the sediment mass (in tons) per hectare, Q: chemical fertilizer, S: only soil, NR: nutritional recommendation.

All treatments had eight repetitions each, and one plant per repetition (Fig. 2). A mass of soil was added to reach 23 kg of substrate (soil + sediment) to the pots of all treatments. The sediment was mixed into the soil manually in the top layer (up to 10 cm). The seeds of maize (*Zea mays* L.), hybrid AG 1051, were sown in plastic pots with 20 L capacity, containing the substrates described in Table 3. The plants were irrigated every other day to reach field capacity, verified by the drainage of water through a plastic tube on the pots' bottom. The drainage of each plant was used to irrigate it again, to avoid the removal of solutes through water exiting the pots.

Figure 2 - Maize plants at 32 days after sowing (DAS) growing in substrates containing only soil (S), soil + São Joaquim's sediment (SJ), soil + São Nicolau's sediment (SN) and soil + chemical fertilizer (Q). The numbers 100, 75, 50 and 25 correspond to the sediment mass (in ton) per hectare.



2.2.2.2 Variables analyzed during the experiment

At 20, 30, 40 and 50 days after sowing (DAS), the following variables were assessed: plant diameter (measured with a digital pachymeter) and plant height (length from the base of the stem, at ground level, to the apex of the plant). At 48 DAS, the following variables were assessed in fully expanded intermediate leaves: net photosynthesis rate (*A*), transpiration (*E*), stomatal conductance (*gs*), internal CO_2 concentration (*Ci*), leaf temperature (*Tf*), and water use efficiency (WUE), given by the ratio between the photosynthesis and transpiration. Measurements of physiological variables were performed using an infrared gas analyzer (LI6400XT, Li-Cor, USA). The measurements took place between 9:00 and 11:00 am, using an artificial radiation source (about 1,800 µmol photons m^{-2} s^{-1} and a CO_2 concentration of 400 ppm). The relative chlorophyll index was obtained with a portable chlorophyllmeter (SPAD 502, Minolta Co, Ltd, Osaka, Japan), on the same leaves used for the measurement of leaf gas exchange. Four measurements per leaf were taken, totaling eight measurements per plant, and the average value was expressed as relative chlorophyll index (RCI).

The plants were harvested at 96 DAS, when the leaf area was measured using an area integrator (Area meter, LI-3100, Li-Cor, Inc. Lincoln, NE, USA). The plants were placed in an oven with forced air circulation at 65 °C until completely dry, for dry biomass determination.

To quantify the nutrient concentrations in the plants, shoot samples were ground in a Wiley type mill. The nitrogen (N) concentration was determined by sulfuric digestion, according to the method proposed by Malavolta et al. (1997), whereas the concentrations of P, S, Ca, Mg, K, Fe, Cu, Mn and Zn were obtained by nitric-perchloric acid digestion. The first two elements were determined by the spectrophotometry method and the others by the atomic absorption spectrophotometry method (Malavolta et al. 1997). With these results, it was also possible to calculate the total nutrients extracted by the plants, by multiplying its concentration by the total dry biomass of shoots.

2.2.2.3 Data analysis

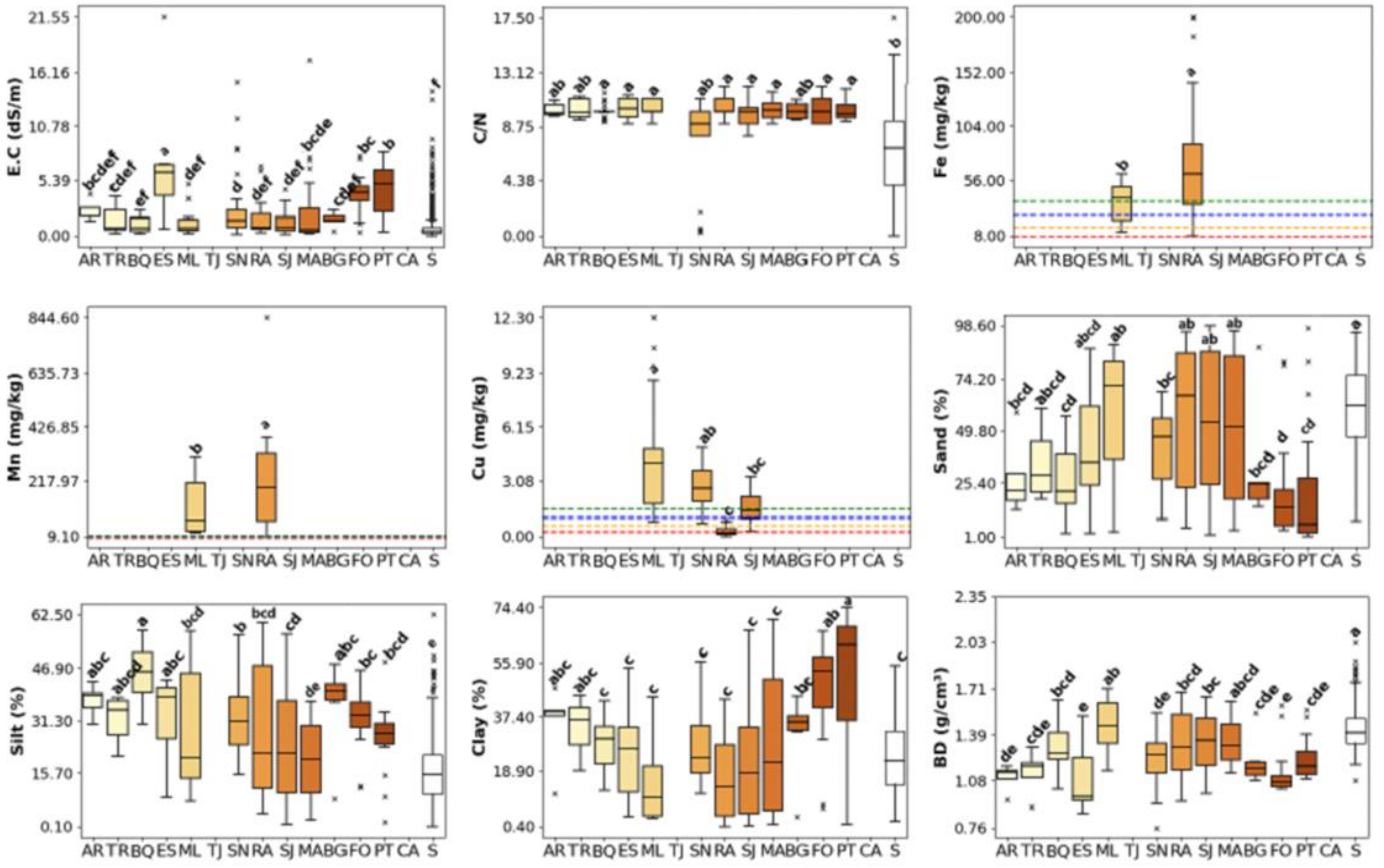
The data for each treatment were submitted independently to analyses of variance (ANOVA), taking into account the doses and different sediment sources, and the means were compared by Tukey's test ($P \leq 0.05$).

2.3 Results and discussion

2.3.1 Physicochemical composition of sediments from surface reservoirs

Based on the sediment database described in section 2.1 we assessed the spatial variability of the sediment physical and chemical properties at regional scale and their heterogeneity (Fig 3). To our knowledge it is the largest sediment database for the study area containing around 280 sediment samples from 14 reservoirs. We believe that it provides a good representation of reservoir sediments in the region, however, it certainly does not provide a complete representation. This section therefore describes and discusses the values contained in the database and implications that the removal of sediment and its subsequent use would have. The sediments were also characterized according to fertility levels as suggested by Mendes (2007). The variance analysis (Table S1) showed that the sediment characteristics could not be clustered by the different basins.

Figure 3 - Physicochemical properties of sediments from surface reservoirs in the semiarid region of Brazilian Northeast. Legend: BD: bulk density. TR, AR, BG, BQ, CA, ES, FG, MA, ML, PT, RA, SJ, SN, TJ and S refer to sediments of Três, Araras, Benguê, Boqueirão, Castanhão, Escola, Fogareiro, Marengo, Mel, Pentecoste, Raiz, São Joaquim, São Nicolau, Tijuqinha and Soil, respectively. Means followed by different letters indicate significant differences at α ≤ 0.05 according to Tukey test. The Lines in red, orange, blue and green represent the fertility level as very low, low, medium, high and very high, respectively, according to Mendes (2007).



Although a high variability of total nitrogen (N) has been found in the analyzed sediments, all samples remained below the reference value of 4.8 g kg^{-1} established by the Brazilian Environment Council in Resolution 454/2012 (Brazil 2012), above which there is the possibility of damage to the environment in the area of sediment disposal. Higher amounts of N were observed in sediments from Castanhão and Tijuquinha reservoirs. This result for Castanhão might be explained by the high residence time of the water in the reservoir: the reservoir has overspilled only twice (2004 and 2009) since the year of its construction (2003) and has been receiving N inputs from anthropogenic activities such as urbanization, agriculture, livestock and in-lake aquaculture, therefore there is an accumulation of the nutrient in the sediment (Molisani et al. 2013). The behavior of N in sediments is difficult to predict (Wu et al. 2008), despite the fact that denitrification, which accounts for 80 to 90% of the process, occurs mainly in sediments (Shaffer and Rönner, 1984).

The content of available P ranged from 7.3 to 91 mg kg^{-1} of sediment and higher values were observed in the sediment from São Nicolau reservoir. In general, the sediment fertility according to this element ranged from very high to medium. It is important to highlight that P values presented in this study represent the fraction of soil assimilable P, i.e. the portion of the nutrient that is easily available to plants. Several studies (Mattei et al. 2017; Tozzi et al. 2021; Kiani et al. 2023) have reported that P availability to plants by sediments is also due to the high level of fine clay particles and organic matter content, which constitute the adsorbed P fraction in soil. However, this fraction has not been analyzed and is highly dependent on environmental factors of the aquatic system, such as pH. The pH and oxygen concentration of the aquatic environment also have an influence on the P fraction bound to elements such as iron, Al, and Ca. Although this P fraction is not available to plants, it is important to evaluate its content, because under anoxic conditions, P can return to the water column, contributing to its eutrophication (Moura et al. 2020; Lima Neto et al, 2022).

P is an essential macronutrient for plant growth, however it mainly originates from non-renewable phosphate rocks. The high consumption of phosphate fertilizers in the agricultural sector and their poor management can lead to the loss of P, causing environmental problems, such as the eutrophication of water bodies. Given this scenario, it is important to close the P agricultural cycle (and restore lakes already eutrophic), through the use of alternative sources of nutrients and organic carbon, such as sediments from the bottom of reservoirs. Reservoirs in semiarid regions have higher nutrient contents in the sediment than in the soil (Braga et al. 2019), in addition to high temperatures throughout the year, high variation in water level due to recurrent droughts and high evaporation rates (Barbosa et al. 2012), promoting in this way the stratification of the water column (Dantas et al. 2008) and the rapid degradation of organic matter. Under these conditions, the bottom sediment is often under anoxic conditions, culminating in a significant release of P into the water. Therefore, the adoption of P as the reference nutrient for setting the sediment dose for fertilization, since high concentrations of this element have been observed in the sediment (Fig 3), could also contribute to controlling water quality of reservoirs (Lima Neto et al. 2022).

According to Dillon and Molot (2005), iron (hydr-)oxides in water and sediments are associated to the catchment’s geology, climatic conditions and soil. Smal et al. (2013) evaluated the bottom sediments of two small reservoirs in Poland and established a strong linear relationship between P content and Fe and Al concentrations in the sediments, implying that high levels of Fe and Al in the sediments may contribute to precipitation of the nutrient to the sediment, instead of its release into the water column. Furthermore, Moura et al. (2020) also concluded that the older the reservoir, the higher the concentration of P-bound Fe and Al in the sediment. The sediments of Mel and Raiz reservoirs are classified as very good fertility according to Fe content, unlike the sediment Al content, which varied from 0.09 to 1 cmol kg-^{1}. In soils with low pH (around 4.3), stronger correlations between Al and OM are typically observed (Nitzsche et al. 2022). Indeed, more acidic sediments, such as those from Araras and Três reservoirs, showed a higher Al content. Under these conditions, Al^{3+} is the most abundant form of this element, significantly impacting plant growth (especially the roots). However, there are reports about the beneficial effects on species as corn, for instance the increasing of leaf growth, when a low dosage of Al is applied (Bojórquez-Quintal et al. 2017).

The high amounts of nutrients, as N, P and Mg in the sediment from São Nicolau reservoir can increase the availability of nutrients for plants, resulting in benefits for crop productivity, as noted in several studies in the literature (Canet et al. 2003, Kiani et al. 2021; Brigham et al. 2021). The C/N ratio is related to organic matter mineralization: the lower the ratio, the higher is the release of available N. In our study, the C/N ratio ranged from 8.2 to 10.2: according to Brust (2019), organic substrates with a C/N ratio below 15 present a rapid mineralization of organic matter and release of N to plants. Kiani et al. (2023) also observed similar values of C/N ratio and Dróżdż et al. (2020) observed a ratio of 12 to composts based on fish pond sediment and wheat straw. Studies found in the literature have already reported the ability of sediments to increase soil fertility due to the high OM content (Brigham et al. 2021; Szara-Bąk et al, 2023), which was also observed for the assessed sediments. In addition, organic matter in the soil is also related to increasing water holding capacity (Darmody and Diaz, 2017), which is a major issue for agricultural production in dry regions like the study area.

There are also reports in the literature of deacidifying effects by bottom sediments with pH around 6.7 (Kiani et al. 2023; Tarnawski et al. 2015), which is particularly interesting due to the limitation of the toxic effect of possible heavy metals and trace elements present in the sediment. The contents of trace elements ranged from 114.5 to 213.6 mg Mn, from 37.4 to 72.8 mg Fe, from 0.3 to 4.8 mg Cu per kg of sediment, values markedly lower than observed by others authors (Canet et al. 2003; Ebbs et al. 2006; Mattei et al. 2018; Baran et al. 2019; Tozzi et al. 2021, Kiani et al. 2021; Kiani et al. 2023). Most of these studies addressed sediments from urban channels or from reservoirs near industrial areas. These results confirm the environmental feasibility of reusing sediment in the study area.

However, a factor that may hamper the use of sediments from reservoirs is their electrical conductivity: sediments with EC higher than 4 dS m^{-1}, as observed for the Escola, Pentecoste and Fogareiro reservoirs, can cause soil salinization and inhibit plant growth (Braga et al. 2017). Thus, EC is one of the key parameters for evaluating the feasibility of sediment reuse, due to its relevance in the study area and easy determination. In contrast, higher fractions of fine particles of soils have been observed in sediments from those reservoirs (Fig. 3). A higher silt and clay content has potential to improve the water retention capacity, which might result in reduced irrigation needs. Also, high organic carbon contents together with high clay fractions in the sediments can increase the cation exchange capacity of the soil (Canet et al. 2003, Brigham et al. 2021). Hence, sediment reuse could help prevent nutrient deficiencies, which are very common in soils with the dominance of the sand fraction (Baran et al. 2019), such as those commonly found in semiarid areas (Ayangbenro and Babalola, 2021).

2.3.2 Effect of sediment as soil conditioner on maize growth and physiology

The relative chlorophyll content in leaves, the stomatal conductance (*gs*), net photosynthesis (*A*), internal CO_2 concentration (*Ci*) and transpiration (*E*) were affected by the treatments throughout the study (Table S2). We also observed a significant influence of the sediment doses added to the soil on the variables mentioned above and of the sediment source on the photosynthesis and internal CO_2 concentration. The relative chlorophyll content in the two treatments with higher sediment doses (SN100 and SJ100) showed higher means compared to the other treatments, and these were also significantly higher than the chlorophyll contents of plants with chemical fertilizer and control treatment (Table 4). Other studies have also verified an increase in chlorophyll in plants growing in substrates amended with sediment (Mattei et al. 2017).

Table 4 - Relative chlorophyll index (*RCI*), stomatal conductance (*gs*), net photosynthesis rate (*A*), internal carbon concentration (*Ci*) and transpiration (*E*) of maize plants at 96 days after sowing (DAS) growing in substrate containing only soil, soil + São Joaquim's sediment, soil + São Nicolau's sediment and soil + chemical fertilizer. The values are represented by the averages.

Treatments	***RCI***	***gs***	***A***	***Ci***	***E***
	-	*mol* $m^{-2}s^{-1}$	$\mu mol\ m^{-2}\ s^{-1}$	*ppm*	*mmol* $m^{-2}s^{-1}$
S	30.7 b[1]	0.099 d	18.4 de	84.9 cd	3.6 cd
SJ25	32.3 ab	0.082 d	14.2 e	95.4 bc	3.0 d
SJ50	33.1 ab	0.161 a	27.3 abc	69.7 d	4.9 ab
SJ75	33.5 ab	0.139 abc	22.1 cd	74.7 cd	4.4 abc
SJ100	36.1 a	0.154 ab	28.7 ab	86.9 cd	4.8 ab
SN25	33.0 ab	0.12 bcd	22.1 cd	110.1 b	4.0 bcd
SN50	32.5 ab	0.115 cd	19.3 de	95 bc	3.4 cd
SN75	33.1 ab	0.162 a	30.1 a	90.1 bcd	4.9 ab
SN100	36.7 a	0.165 a	29.3 a	78.9 cd	5.2 a
Q	30.4 b	0.146 abc	22.6 bcd	136.4 a	4.5 abc

Legend: [1] Means followed by the same letter in the column do not differ by the Tukey test ($p > 0.05$). Legend - SN: São Nicolau's sediment, SJ: São Joaquim's sediment; the numbers 100, 75, 50 and 25 correspond to the sediment mass (in tons) per hectare, Q: chemical fertilizer, S: only soil.

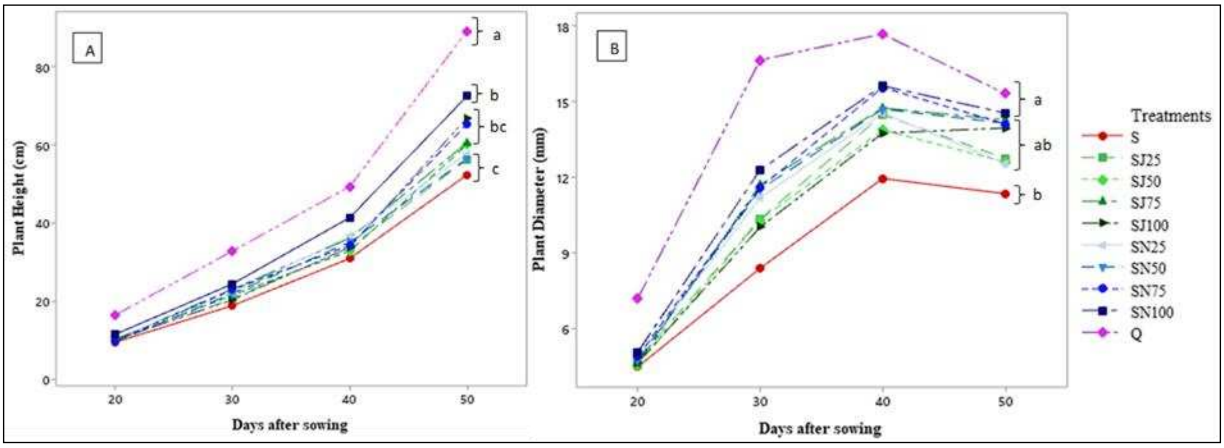
The chlorophyll content is an important parameter for plants, because the amount of solar radiation absorbed by a leaf is directly related to the concentration of photosynthetic pigments (such as chlorophyll a and b). Thus, the chlorophyll concentration in leaves represents a photosynthetic activity indicator, and a reduction in the levels of this pigment can cause a decrease in primary production (Curran et al. 1990). Furthermore, this parameter is influenced by the N concentration, as it is a response of the crops to the nutrient availability in the soil / substrate (Minotta and Pinzauti, 1996). According to Agegnehu et al. (2016), high chlorophyll concentration suggests higher nutrient and water availability as observed in this study. Agegnehu et al. (2015) also showed significant increases in leaf chlorophyll content of maize when biochar was added to the soil.

Plants growing in the treatments with higher sediment doses (SN100 and SJ100) presented significantly higher values for stomatal conductance, net photosynthesis rate and transpiration. Maize is a species with a C4 photosynthetic metabolism (Taiz et al. 2017; Bhatla and Lal, 2018): from the subclassification according to the decarboxylative enzyme of C4 plants, maize belongs to the one with the highest photosynthetic efficiency, i.e. the plant achieves high rates of CO_2 assimilation while low amounts of water are lost by transpiration (Freitas, 2020). Higher stomatal conductance is, in general, related to higher transpiration (Taiz et al. 2017; Bhatla and Lal, 2018) and this behavior was observed for the plants that grew in substrate containing sediment. This result shows that these plants were more photosynthetically active, corroborated by the higher net photosynthesis rate, which may have occurred due to the water retention by the sediment that was added to the top layers of the substrate.

It is important to note that, before the incorporation of the sediment to the soil, the latter presented only 53% of the N contained, for example, in São Nicolau's sediment. It is possible that this difference increased even more due to the process of adding sediment to the soil (sieving and stirring), which promoted the aeration of the material and, consequently, possibly the N release by organic matter mineralization (Kiani et al. 2021). On the field scale, this process could occur during the preparation of the agricultural field by plowing and harrowing the soil. Soil preparation is also recommended to avoid a possible waterproofing layer, due to the addition of sediments with high clay content, thereby decreasing water infiltration capacity. The low sediment C:N ratio (Table 2) confirms the idea of relatively fast decomposition of organic matter in the sediment material (Urbaniak et al. 2019). Thus, higher leaf chlorophyll contents and therefore higher photosynthetic efficiencies of plants growing in substrates containing sediment were observed.

Plant growth, leaf area, and biomass production of maize were significantly influenced by the amount of sediment added to the soil, the latter variable being further influenced by the source of sediment and its interaction (Table S2). Plant height is an important characteristic because it is usually positively related to crop production (Greveniotis et al. 2019), therefore it can be used as an indicator of crop yield. Water and N availability are the main factors associated with vegetative growth. So, water shortage and/or N deficiency reduces the number of leaves, leaf area, stem diameter, and plant height (França et al. 2011; Campelo et al. 2019). In general, the addition of sediment to the soil caused an increase in plant height, which was proportional to the amount of material added, especially when sediment from the São Nicolau reservoir was used (Fig 4A). However, the addition of chemical fertilizer to the soil promoted higher plant height growth compared to the other treatments containing sediment. Mattei et al. (2017) also observed increased plant height of *Photinia x fraseri* growing in substrate containing dredged sediment from the Navicelli canal, Italy, even when compared to plants growing in substrate containing organic compost (peat).

Figure 4 - Plant height (A) and stem diameter (B) of maize plants at 20, 30, 40 and 50 days after sowing (DAS) growing in substrate containing only soil, soil + São Joaquim's sediment, soil + São Nicolau's sediment and soil + chemical fertilizer. The points represent the mean values of 8 repetitions. Means followed by the same letter in the column do not differ by the Tukey test ($p > 0.05$). SN: São Nicolau's sediment, SJ: São Joaquim's sediment; the numbers 100, 75, 50 and 25 correspond to the sediment mass (in tonne) per hectare, Q: chemical fertilizer, S: only soil.

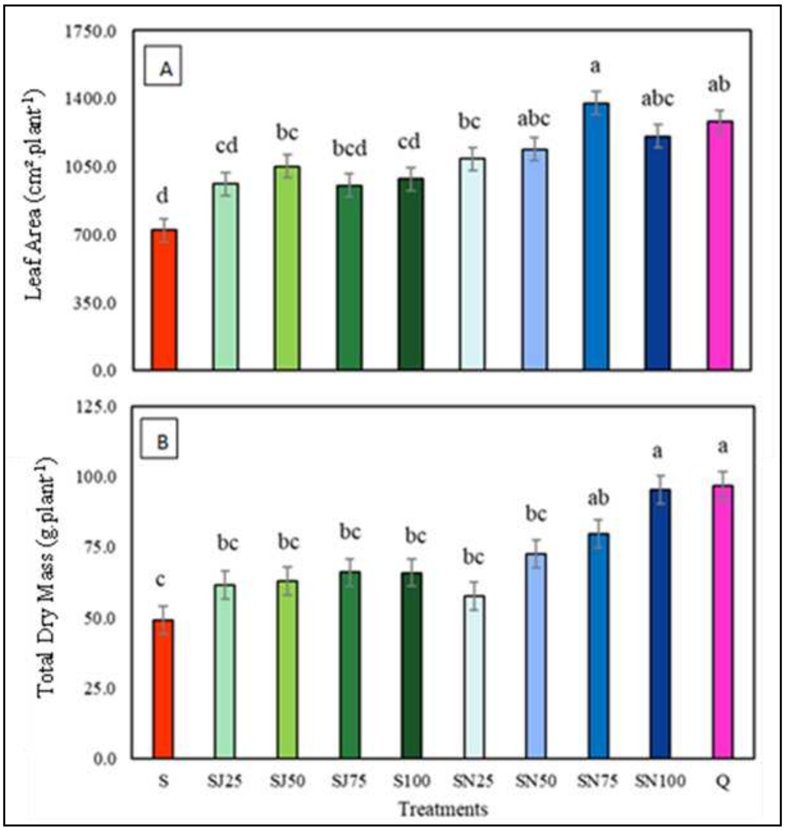


Regarding stem diameter (Fig 4B), the plants growing in the substrates with the two highest doses of São Nicolau's sediment (SN75 and SN100) presented, at 50 DAS, significantly different averages from the plants growing in the substrate without sediment, and did not present significant differences to the diameters of the plants growing in substrate with chemical fertilizer. As observed in Table 2, São Nicolau's sediment presented higher concentrations of macro and micronutrients, as well as organic matter, than the sediment from the São Joaquim reservoir. It was also found that between measurements taken at 40 and 50 DAS, there was a decrease in plant diameter, which was more evident in the chemically fertilized treatment. Reductions in stem diameter are related to the translocation of photo-assimilates for grain production, a period in which the crop requires a large amount of water and nutrients (Magalhães and Durães, 2006).

Chemical fertilizers provide nutrients in ionic form, which is more easily absorbed by plants (Elemike et al. 2019). This may have contributed to the higher vegetative growth of plants with the use of fertilizers, particularly in the early stage of development, when compared to the use of sediments. For the latter, the organic N must be mineralized into inorganic N before it can be absorbed and used by crops (Sharifi et al. 2008). Furthermore, addition of sediments with high clay and organic matter contents, such as from the São Nicolau reservoir (Table 2), can increase the water retention and soil microbiological activity (Silva et al. 2012; Crusciol et al. 2019), contributing to increase nutrient availability and to faster plant growth.

The addition of sediment from the São Nicolau reservoir promoted larger leaf areas in the maize plants, with a difference of about 80% in the treatment with 1.8 kg (or 75 ton of sediment per hectare) of São Nicolau's sediment, compared to the control treatment (Fig 5A). However, no significant differences were observed between plants growing in substrate with different doses of sediment from this reservoir.

Figure 5 - Leaf area (A) and total dry mass (B) of maize plants at 96 days after sowing (DAS) growing in substrate containing only soil, soil + São Joaquim's sediment, soil + São Nicolau's sediment and soil + chemical fertilizer. Values are represented by the mean ± standard error. Means followed by the same letter in the column do not differ by the Tukey test ($p > 0.05$). SN: São Nicolau's sediment, SJ: São Joaquim's sediment; the numbers 100, 75, 50 and 25 correspond to the sediment mass (in tonne) per hectare, Q: chemical fertilizer, S: only soil.



Addition of sediment to the substrate also impacted the plants' biomass: the dose of sediment, the source, and the interaction between the two factors, significantly influenced the maize dry matter production (Fig 5B). The two treatments with most sediment from the São Nicolau reservoir (SN75 and SN100), showed averages of total dry mass that were 62% and 94% higher than the control treatment, respectively, and did not differ significantly from plants having chemical fertilizer as a source of nutrients. Similar results were observed by Kiani et al. (2021) for dry matter production of the species *Lolium perene L.* and by Canet et al. (2003) for lettuce growing in soil containing sediments from lakes Mustijärv (Estonia) and Albufera (Spain), respectively. In this study, the results show that the addition of sediment to the soil can increase biomass production of maize plants by up to two-fold.

The improvements in crop performance obtained in our work obtained from the addition of sediment to the substrate are consistent with other studies (Canet et al. 2003; Fonseca et al. 2003; Mattei et al. 2017; Kiani et al. 2021) and can be attributed to the higher nutrient availability, but also to moisture associated to the fine particles of the sediment. Due to the high concentration of available P in the São Nicolau's sediment, the P mass added to the soil in the SN100 treatment was even higher than in the treatment with chemical fertilizers (Table 3). This high content of P is related to high clay and Al and Fe concentrations in the sediment, leading to a long-term mobilization of the P (Laakso et al. 2017). Additionally, other macronutrients (Ca and Mg) and micronutrients are present in the sediment, but not in the NPK-based chemical fertilizers. These nutrients can promote a rich and varied microbial community (Brigham et al. 2021). Furthermore, Canet et al. (2003) have observed that adding sediment to the soil may cause an increase in the cation exchange capacity due to high concentration of organic matter, together with the clay content, thus reducing the consequences of possible soil micronutrient deficiencies to plant growth. Although we did not analyze cation exchange capacity in our study, this effect cannot be neglected considering the higher organic matter and clay content of the sediments compared to the soil of the same region.

Table 5 shows the sediment effect on the macro and micronutrients extraction by maize plants. The different sediment doses resulted in significant differences for the nutrients N, P, B, Cu and Fe, while the sediment source promoted differences for the macronutrients (except N), Cu, Mn and Zn (Table S3). In general, it was found that the nutrients analyzed were extracted in the following decreasing order: K > N > Ca > Mg > P > S > Fe > Zn > Mn > B > Cu. Such information is relevant, for example, for soil fertilization recommendations, enabling to increase plant efficiency and reducing production costs (Mendonça et al. 2014). The total nutrients extracted by maize depend on several factors, including the variety, the weather of the region, soil fertility and crop management (Maggio, 2006). Taiz et al. (2017) argue that the processes of nutrient accumulation and mobility within the plant may be related to the variations in nutrient contents at 90 DAS of maize.

Table 5 – Macro and micronutrients extraction of maize plants at 96 days after sowing (DAS) growing in substrate containing only soil, soil + São Joaquim's sediment, soil + São Nicolau's sediment and soil + chemical fertilizer. Values are represented by the mean.

Treatment	***N***	***P***	***K***	***Ca***	***Mg***	***S***	***B***	***Cu***	***Fe***	***Mn***	***Zn***
	g.plant^{-1}						*mg.plant^{-1}*				
S	0.34 c	0.06 d	0.49 c	0.20 b	0.14 c	0.05 c	1.26 c	0.30 ab	9.90 ab	1.13 c	2.18 b
SJ25	0.35 bc	0.06 d	0.73 bc	0.22 b	0.16 bc	0.05 bc	1.31 c	0.30 ab	8.63 ab	1.48 bc	2.49 ab
SJ50	0.44 abc	0.07 bcd	0.75 bc	0.24 b	0.18 abc	0.05 abc	1.58 bc	0.09 c	6.08 b	1.32 bc	2.38 ab
SJ75	0.57 a	0.09 bcd	0.84 abc	0.28 ab	0.19 abc	0.06 abc	1.64 abc	0.16 bc	7.43 ab	1.49 bc	2.45 ab
SJ100	0.55 ab	0.08 bcd	0.70 bc	0.25 ab	0.18 abc	0.05 abc	2.11 ab	0.37 a	6.64 ab	1.73 abc	2.46 ab
SN25	0.44 abc	0.08 bcd	0.74 bc	0.26 ab	0.19 abc	0.05 abc	1.93 ab	0.31 ab	7.32 ab	1.73 abc	2.63 ab
SN50	0.51 abc	0.10 b	0.84 abc	0.29 ab	0.19 abc	0.07 abc	2.20 a	0.35 a	6.59 ab	1.68 abc	3.02 ab
SN75	0.56 a	0.09 bc	1.00 ab	0.30 ab	0.21 abc	0.06 abc	2.01 ab	0.43 a	6.69 ab	1.89 abc	2.91 ab
SN100	0.54 ab	0.10 b	1.15 a	0.36 a	0.22 ab	0.06 abc	1.93 ab	0.45 a	10.39 a	2.02 ab	3.20 a
Q	0.59 a	0.14 a	1.23 a	0.36 a	0.24 a	0.08 a	2.20 a	0.43 a	8.96 ab	2.34 a	2.87 ab

Legend: [1]Means followed by the same letter in the column do not differ by the Tukey test ($p > 0.05$). SN: São Nicolau's sediment, SJ: São Joaquim's sediment; the numbers 100, 75, 50 and 25 correspond to the sediment mass (in tons) per hectare, Q: chemical fertilizer, S: only soil

In general, there were no differences in nutrient extraction between the treatment with the highest dose of São Nicolau's sediment (SN100) and the treatment with chemical fertilizer, except for P, for which the highest extraction was observed on the latter treatment. Furthermore, N and Mg extraction were 58% higher for the SN100 treatment when compared to the control treatment (only the soil from the region). The control treatment also showed similar averages as the other treatments for Fe extraction. This behavior is similar to that observed by Kiani et al. (2021) for ryegrass. For P and Ca, the SN100 treatment increased the extraction of nutrients by 64% and 80%, respectively, compared to the control treatment. K extraction increased with the increase of the sediment dose, with the SJ100 treatment being similar to the treatment with chemical fertilizer. The extraction of this macronutrient had a 2.5-fold increase due to the addition of 2.4 kg (100 t.ha^{-1}) of São Nicolau's sediment. No effects of sediment addition were observed on the extraction of K, S, and Mn in plant tissues of bluegrass by Kiani et al. (2021) and on the P content of tomatoes by Canet et al. (2003).

However, the potential benefits of reusing sediment as a nutrient source for agricultural purposes depend on both the source / nature of the sediment and the soil properties (Renella, 2021). Wariness is needed regarding the content of contaminants, such as heavy metals, in the sediment (Canet et al. 2003; Leue and Lang, 2012; Mattei et al. 2017; Tozzi et al. 2019), which may prevent its use for this purpose depending on the concentration and origin of contaminants. In our previous studies in the semiarid region of Brazil (Braga et al. 2017; Braga et al. 2019; Lira et al. 2020; Carvalho et al. 2022), we found no contaminants in the sediment that could hamper the growth of crops. Regarding copper concentrations in sediments from the bed of surface water referred to in the literature, values of 10.5 to 200 mg kg^{-1} have been observed (Leue and Lang, 2012; Tarnawski et al. 2015; Kiani et al. 2021). The concentration observed in this study was 2 mg of Cu kg^{-1} of soil (Table 2), thus demonstrating that a possible contamination by heavy metal is unlikely due to the land use in the region where the reservoirs are located, which is mostly for subsistence farming. Moreover, similar averages for the extraction of this element were observed in plants in the treatments with sediments compared to the plants from the control treatment. Contrarily, Tarnawski et al. (2015) observed linear increases in the concentration of copper in the roots and stem of maize plants with increasing sediment doses incorporated into the soil. For the elements Zn and Mn, the values observed in this study were similar to those found in the literature (Baran et al 2019; Kiani et al. 2021; Szara-Bąk et al. 2023). It is important to point out that the maximum levels of trace elements allowed in feed for Cu and Zn are 30 and 100 mg kg^{-1}, respectively (Kabata-Pendias et al. 1993), showing that the sediment reuse as a soil conditioner to agricultural production appears to be safe. However, in case of industries and large-scale non-organic agricultural production existing nearby a reservoir, previous detailed analysis of the sediment is recommended before its reuse for agricultural purposes.

The electrical conductivity can also hamper the reuse of sediment in the substrate for plant cultivation, as observed by Braga et al. (2017) in our study region. Canet et al. (2003), working with a sediment with 2 dS m^{-1}, observed considerable increases in electrical conductivity or harmful ions such as Cl^- or Na^+, even at low sediment application rates. In this study, we observed electrical conductivity of 0.8 dS m^{-1} for the sediments and it seems there was no negative effect on the plants related to salinity. Thus, the authors stress the need to determine the sediment's electrical conductivity before cultivation, or that appropriate rates of irrigation should be adopted after sediment addition to promote leaching of eventual excess salts.

In general, the sediment from São Joaquim reservoir presented lower concentrations of organic matter and nutrients as compared to the São Nicolau reservoir, and the statistical analyzes indicate no positive impact when adding sediment from the former to the soil. Higher sediment mass from São Joaquim could be tested, aiming to reach nutrient concentrations similar to the São Nicolau treatment. In terms of N and K, it would take up to 1.5 times more sediment from the São Joaquim to achieve such nutrient amounts. However, the maximum sediment doses adopted by us were defined according to the economic feasibility of reusing sediment in the study area, as proposed by Braga et al. (2019), i.e. although higher sediment doses from São Joaquim might be technically feasible, they are not economically justified.

The practice of sediment reuse has been proposed as an alternative to the traditional soil fertilization with synthetic fertilizers (Nixon, 2003). The production of synthetic fertilizers involves considerable environmental and economic impacts (Mattei et al. 2017). Also, according to Chapman et al. (2016), due to a 75% reduction of sediment input into the Vietnamese Mekong Delta, about $15 million more will be spent on fertilization of rice crops in the region. In our study region, it has been demonstrated that the costs of excavating the nutrient-enriched sediments from the bed of empty reservoirs and transporting them to crop fields are of the same order of magnitude as using N-based mineral fertilizers (Braga et al. 2019). Indeed, according to the same authors, the sediment reuse practice can generate savings of up to 30% when compared to traditional fertilization, directly benefiting the livelihood of diffuse communities depending on small-scale agriculture.

The application of sediment to agricultural fields shows positive effects on several soil fertility parameters by increasing the content of macro and micronutrients, organic matter, cation exchange capacity and soil organic carbon (Fonseca et al. 2010; Leue and Lang, 2012; Tarnawski et al. 2015; Kiani et al. 2021) and the practice is in line with the circular economy policy. Moreover, the addition of this material, which has a predominance of finer soil particles such as silt and clay, can improve sorption properties and soil structure, suggesting its relevance especially in the case of nutrient-poor or degraded soils (Sigua et al. 2004; Yozzo et al. 2004; Capra et al. 2015; Brigham et al. 2021). The potential increase in water retention capacity by the addition of fine particles is another key issue for the agricultural sector, as it might reduce the need for irrigation and protect crops against the effects of water deficit (Canet et al. 2003).

2.4 Conclusion

The analysis of the sediment's physicochemical properties showed the enrichment of nutrients, organic matter and fine particles in this material. For instance, the concentration of N and K in the sediment were 3 to 10 times higher in the sediment (compared to soil) and the organic matter content up to 6 times higher. The high concentration of other nutrients, such as Ca and P, in the sediment reveals the possibility of its use as a source of nutrients for plants, with the sediment reuse representing a way to close the cycle of P in agriculture. The hypothesis was confirmed by the experiment on maize plants, since the plants growing in substrate containing sediment showed higher levels of chlorophyll and photosynthesis rate, as well as similar biomass production of the plants with the largest dose of São Nicolau’s sediment and the treatment with chemical fertilizer.

Due to the high spatial variability of the sediment's physicochemical properties, a prior analysis is required to set the most appropriate dose and avoid soil contamination, mainly for future practical applications. As an example, heavy metals and electrical conductivity might prevent the use of sediments for agricultural purposes. Although the copper concentration in the sediments sampled indicates that there are no potential problems of environmental contamination, 20% of the sediments evaluated presented values above the maximum recommended limit (4 dS m^{-1}). Studies are also recommended on the association of chemical fertilizers and the rapid release of nutrients, in contrast to sediment, which makes nutrients available over a longer period of time and, according to the literature, have shown lower nutrient losses by leaching. The potential benefits of the sediment reuse practice are not limited to the improvement of the physical and chemical characteristics of the soil, as addressed in this study: in addition, it may represent an alternative to increase the production of family farming, reducing the costs with fertilizers and generating income and employment in rural areas.

As an outlook, we propose further investigations regarding the steps needed to scale up this process to the field scale and turn it into policy, such as the assessment of the willingness of farmers to adopt the practice and assessment of the applicable legislation. In addition, mapping the nutrient content in soils and sediments from hyperspectral satellite images should contribute to scale up the practice by providing information to society on which reservoirs are more suitable. Findings on the potentials and limitations of the sediment reuse practice have been discussed with stakeholders and disseminated among farmers in the study area within the Chief Scientist Program of the Ceará Federal State.

3 CHAPTER II: REUSE OF SEDIMENTS FROM SURFACE RESERVOIRS FOR AGRICULTURAL PRODUCTION IN THE BRAZILIAN SEMIARID REGION: SPATIO-TEMPORAL VARIABILITY, EXTRACTION CONDITIONS, ECONOMIC ANALYSIS AND REGULATORY BARRIERS

Abstract: This study explored the potential of sediment reuse from surface reservoirs located in the Brazilian semiarid region as a soil conditioner for agricultural production, to reduce the demand for high-consumption chemical fertilizers through sediment replacement, while taking into account the sediment variability, the economic and environmental benefits and regulatory barriers for applying the practice. The database presents results for sediments sampled from 10 reservoirs located in the Brazilian semiarid region. We also conducted a cost-benefit analysis of reservoir sediment reuse, in face of the latest global economic crisis. The analysis of the reservoirs' volume dynamics showed that the sediment has been exposed frequently and for long time periods, enabling its excavation. The reuse of sediments from reservoirs' beds in agriculture can increase crop yields and has potential to substantially benefit the environment and society. However, the spatio-temporal variability of the physical-chemical characteristics of the sediment may be an obstacle to extending the practice. In the reservoirs included in this study, the analysis of heavy metals and trace elements showed that the material is not contaminated, decreasing the risk of negative environmental impacts of the practice. In Brazil, it is necessary to establish guidelines and regulations in order to ensure that the sediments are reused in the best and safest way.

Keywords: sustainable agriculture, food security, deposited soil reuse, nutrients cycling.

3.1 Introduction

By 2050, the projected increase in the world's population to 9.5 billion people (Azuizion, 2020) is expected to result in significant strain on the global food system to keep up this demand, while the sustainability of the agricultural sector has also been put to test (Zou et al., 2022). Therefore, it is essential to develop strategies that result in a more sustainable agricultural production, without losing efficiency.

Increased demand for food has traditionally been achieved by increasing the use of chemical fertilizers, but this approach may lead to significant greenhouse gas emissions and water contamination (Bouwman et al., 2017; Fink et al., 2018). For instance, according to Zou et al. (2022), the global application of P fertilizers on croplands has already exceeded the estimated planetary limit, thus it becomes increasingly important to close the agricultural P cycle. Other studies have shown that the efficiency of chemical fertilizers application has decreased and that crops can absorb a maximum of 50% of the chemical fertilizers applied (Wang et al., 2018). This means that a large amount of these components is lost by leaching, resulting in excess nutrients in adjacent water bodies and groundwater, thus contributing to eutrophication and threatening the health of aquatic organisms and humans.

Spadaro and Rosenthal (2020) indicate the reuse of sediment from the bed of lakes as a way to meet the circular economy model, especially for P. The removal of reservoir sediments not only improves public health but also extends the reservoir's life (Kondolf et al., 2014) and can contribute to keep water quality at acceptable levels (Lira et al., 2020). Numerous studies suggest that bottom sediments from lakes can be used as soil conditioner, by incorporating nutrients for agricultural production or as a supplement to chemical materials traditionally used for soil fertilization (Fonseca et al., 2003; Sigua 2009; Baran et al., 2012; Braga et al., 2017; Ebbs et al., 2006; Tarnawski et al. 2017; Baran et al. 2019a). Sediment characteristics such as high contents of macronutrients in bioavailable forms, organic matter and fine soil fractions have shown to improve the structure and sorption properties of soils (Canet et al. 2003; Tarnawski et al. 2015; Renella 2021; Kiani et al. 2021), water holding and cation exchange capacity (Brigham et al., 2021).

In semiarid regions such as the Brazilian northeast, a very peculiar condition favors the sediment reuse: the dense network of surface reservoirs developed for water supply (de Araújo and Medeiros, 2013) and the occurrence of long periods of drought (Zhang et al., 2021). These two characteristics result in the frequent dry-falling of reservoirs with large amounts of sediment becoming available by cheap and easy techniques such as excavation. However, the benefits of using sediments in agriculture depend on their physicochemical (Braga et al., 2019) and ecotoxicological properties (Kiani et al., 2023). As sediments can contain potentially toxic trace elements and organic pollutants at different levels (Baran et al. 2019b; Ferrans et al. 2019), it’s mandatory to evaluate their properties to determine the need for some treatment, management and potential applications of sediment (Baran et al., 2019c). It is also essential to establish guidelines and regulations to prevent negative environmental impacts from the reuse of sediments (Heise, 2018). Renella (2021) stressed the importance to reconsider nutrient-rich recycled sediments as a component material category in the new EU regulation on fertilizers (https://eur-lex.europa.eu/eli/reg/2019/1009/oj).

Lastly, the reuse of sediments in agriculture could be an alternative source of nutrients and organic carbon to ensure global food security. Food security is characterized as the access to safe and sufficient food, however it is extremely affected by economic market and environmental limitations, such as climate change and water availability (Rad et al., 2021). The COVID-19 pandemic has wrecked damage on the global economy, as a result of global lockdowns and the increased costs in the health sector to control the disease (Meuwissen et al., 2021). In addition, consumers and producers have faced difficulties, such as the restrictions on food imports and exports, that eventually led to a remarkable rise in the fertilizer prices, reducing incomes for farmers, and notably damaging the agricultural sector, with short- and long-term effects on food security around the world (Rivington et al., 2021).

This study explored the potential of reusing sediments from surface reservoirs located in the Brazilian semiarid region, as a soil conditioner for agricultural production, to reduce the demand for high-consumption chemical fertilizers through sediment replacement. Therefore, (1) we assessed temporal changes by re-sampling and analyzing sediment from previously sampled locations (5 years later), (2) updated our cost-benefit analyses with respect to current price developments, (3) assessed legislation on different aspects related to sediment excavation, application and contents, such as nutrients as well as contaminants, and (4) modeled the mass of sediment - and thus nutrients - deposited annually. In addition, we highlight some potential beneficial aspects of the practice with respect to carbon footprint and the development of a tool that brings the findings of our scientific research more accessible to small farmers in the study region.

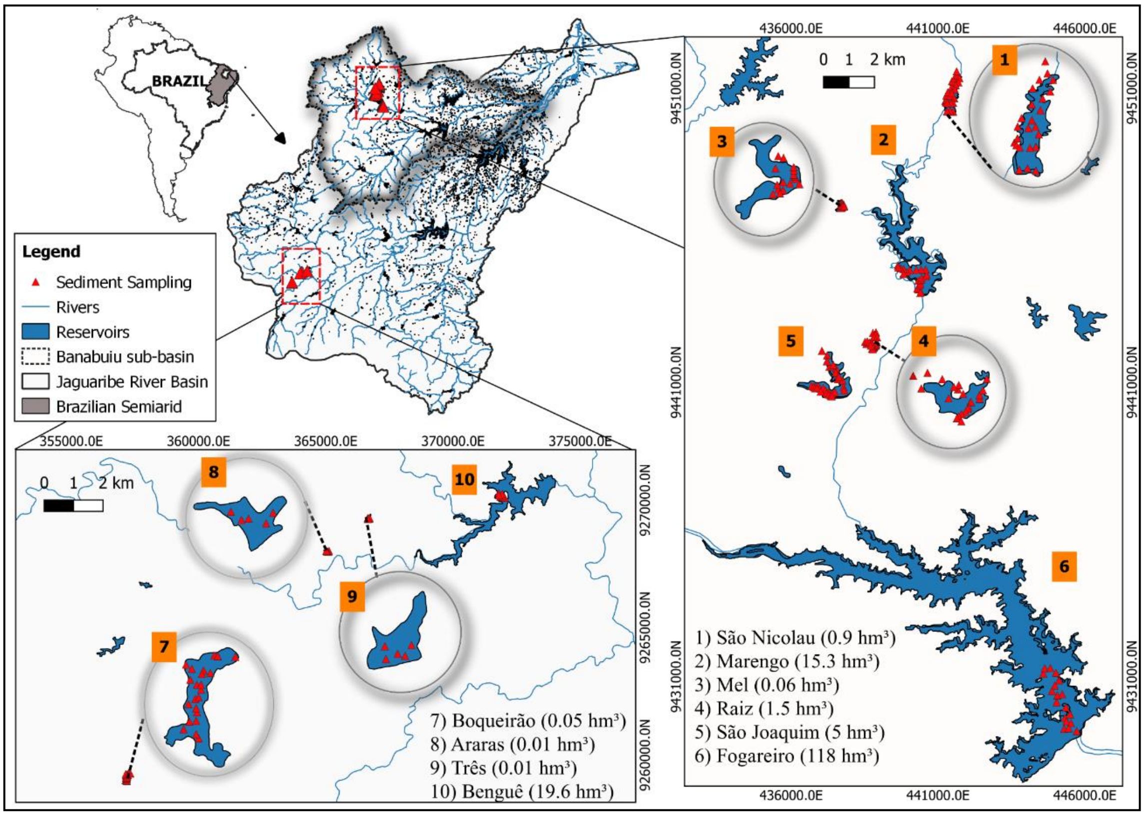
3.2 Materials and methods

3.2.1 Study area

The Jaguaribe river basin (JRB), with its approximately 610 km of length, has an extensive drainage basin that covers more than 75,000 km^2 in northeastern Brazil (Fig. 1a). The basin is characterized, according to the Köppen climate classification, by a semiarid climate, with potential annual evaporation around 2,200 mm and average annual precipitation ranging from 500 mm to 900 mm, with approximately 95% of this precipitation occurring from January to June (Alves et al., 2012). One of the notable characteristics of the Jaguaribe River is its great variability in interannual and intrannual discharge. In a short period of time, the river's flow can vary from 7,000 m^3/s to zero, during intense droughts (Campos et al., 2013). The geology of the JRB is predominantly formed by crystalline complexes (85% of the area), with few sedimentary (15%), and therefore the groundwater supply is represented mainly by fissure aquifers. The predominant soils are lithosols, luvisols, and argisols (COGERH, 2009). Despite its water scarcity, which is strongly associated with rural poverty, water is transferred from the JRB carries to regions with a higher payment capacity through hydraulic structures such as canals, tunnels, and pumping stations (Medeiros and Sivapalan, 2020). The generally shallow soils and the high temporal variability of rainfall have led to the construction of dams, generating a dense reservoir network, with more than 3,000 reservoirs with surface areas larger than 5 ha (Pekel et al., 2016) in the basin, built spontaneously by the community as adaptation to prolonged droughts (Pereira et al., 2019).

Due to the high spatio-temporal variability of the precipitation and a predominance of soils and geology with low water storage capacity, dense networks of dams were developed in the study area (de Araújo and Medeiros, 2013). This was a crucial drought coping measure for the livelihood of population living around these infrastructures (Medeiros and Sivapalan, 2020). Such reservoirs have a social role of promoting better water distribution, allowing that remote rural population have access to the water system and improving their quality of life, besides energy rationality (Nascimento et al., 2019), once gravity center of the water availability is higher than it would be without the network. The Banabuiú catchment, for instance, has a large number of small and unmonitored reservoirs (about 1 reservoir/6 km^2) (Braga et al., 2019) and the regulatory agencies monitor the volume of only 19 large/middle-sized reservoirs. Therefore, there is a lack of observational data on the water dynamics and volume stored in the water bodies, particularly the smaller ones.

Figure 1 - Location of Jaguaribe River Basin (JRB).



3.2.1 Sediment database

In this study we use a database composed of the results from several sediment sampling campaigns conducted by our research group since 2013. These campaigns covered an extensive study area, involving the sampling of sediments in more than 200 points distributed in 11 selected reservoirs and 6 of them are located in the Banabuiu catchment (Fig. 1). The Banabuiu catchment represents 30% of the JRB. The objective of these systematic samples was to obtain a comprehensive representation of the sediment characteristics present in the investigated reservoirs, as well as to verify possible limitations of the sediment reuse as a soil conditioner. The data obtained in these campaigns provide a solid basis for the analysis and understanding of hydrosedimentological processes and are essential for the evaluation of the feasibility of sediment reuse in small-scale agriculture in the Brazilian semiarid region. Details about the sediment sampling and analysis process are reported by Braga et al. (2023).

3.2.3 Accessibility for sediment extraction in the Banabuiú catchment

In order to demonstrate the hydrological behavior of the study region, water storage data on nineteen reservoirs of the Banabuiú catchment has been collected since 2004 (COGERH, 2023). Currently, this information is available on: http://www.hidro.ce.gov.br/, from the Company of Water Resources Management of Ceará (COGERH) and the Foundation of Meteorology and Water Resources of Ceará (FUNCEME) websites. Such information has been essential to understanding the hydrological dynamics of reservoirs located in the basin, particularly during droughts, when the bed sediments are exposed and accessible for excavation.

3.2.4 Spatio-temporal variability of sediment's properties

To monitor temporal changes in the physicochemical characteristics of sediment, we compare the results of sediment analysis sampled at the same points in two campaigns (in 2016 and in 2021) carried out at the São Joaquim and São Nicolau reservoirs from the original sampling locations. Through this time, the reservoir's varied from nearly empty to partially flooded. Sentinel-2 satellite images of November (when cloud free images could be acquired) of each year between 2016 and 2021 were used for evaluating the evolution of the inundation area of the reservoirs. Statistical ANOVA at a significance level of 0.05 was used to assess whether the temporal changes in the physicochemical properties of the sediments were significantly different.

3.2.5 Economic analysis of the sediment reuse practice

In order to assess the temporal variability of the sediment reuse technique for soil fertilization and its vulnerability to the fertilizers market, an update of the fertilization costs (CONAB, 2021) presented in our previous study (Braga et al., 2019) was performed. The costs associated with the sediment reuse consist mostly of its physicochemical analysis, excavation from the reservoirs' bed and transport to the crop field (including equipment rental, fuel and operation). In the study area, the Infrastructure Secretary of Ceará State (SEINFRA/CE) presents reference values for the transport of soils for public works, which depend on the Average Transport Distance of sediments, which for the Banabuiu watershed is 2.3 km (Braga et al., 2019). The volume of sediment needed to fertilize the soils was computed to meet the requirement of maize crop for nitrogen. Furthermore, in this study, we include the cost of the environmental permitting to reservoir desilting. On the other hand, the costs of traditional fertilization consist mainly of the fertilizers purchase, which are influenced by the market and supply chain, and the costs to transport the chemical fertilizers that are regulated by the Brazilian Transportation Agency (Resolution n° 5820/2018). Table 1 summarizes the cost evolution from 2019 to 2023 of the two techniques in relation to 2018 values. In Supplementary Material (Table S1), the detail costs of each technique between 2018 and 2023 are shown.

Table 1 - Increase of the costs of sediment reuse and traditional fertilizing from 2019 to 2023 in relation to 2018.

Technique	**Product/ service**	**Price increase (%)**				
		2019	**2020**	**2021**	**2022**	**2023**
Conventional Fertilization	N fertilizer	10	15	93	183	162
	P fertilizer	18	-19	57	149	278
	K fertilizer	29	28	142	321	316
	Transport of chemical fertilizers	2	7	7	50	50
Sediment reuse	Sediments' physicochemical analysis	0	0	33	33	33
	Sediment excavation, load, transport and discharge	8	8	20	20	20
	Environmental permitting*	100	100	100	100	100

*The environmental permitting was not computed in our previous study (Braga et al., 2019), therefore this represents an extra cost on the values from 2019 to 2023.

3.2.6 Legislation on sediment reuse in agriculture

In spite of the numerous studies on the applications of sediment reuse, there is a legislative lack to regulate the practice in the agricultural sector (EU, 2019; Macci et al., 2022). In the Brazilian semiarid region, although the practice of crop cultivation in areas of nutrients accumulation is a traditional technique by the local population - the so-called 'vazante' planting (de Araújo, 2004) -, there is not yet specific legislation to regulate the use of sediments for soil fertilization, which leads to a misuse of this resource. Across several EU countries, which together produce around 200 million m³ of sediments removed from diverse waterbodies per year (Macci et al., 2022), different approaches for classifying the quality of bottom sediment are being developed (Heise, 2018), but only Finland, Slovakia and Czech Republic have established limits of contaminants for direct use of this material. Considering this scenario, we compared the zinc and copper content of sediments from our database with the limits of contaminants established by the available legislations (Kiani et al., 2021; Macci et al., 2022) and the limit value for sediment disposal in soils according to the Brazilian legislation (CONAMA, 2012).

3.2.7 Availability of macronutrients by sediments from surface reservoirs

The mass of macronutrients (N, P and K) in the sediment from surface reservoirs was computed on a yearly basis for the Banabuiu catchment and the JRB, as the product of the annual silted sediment mass by the mean nutrient content. To estimate the silted sediment mass in the surface reservoirs located in the Banabuiu catchment and JRB, we scale-up the methodology of our previous study (Braga et al., 2019), which used the model proposed by Lima Neto et al. (2011):

$$\Delta M_j = V_{o,j} \xi_m R_j \tag{1}$$

$$R_j = 67.355 \left(\frac{P^2{}_m}{P}\right)^{0.85} \tag{2}$$

Where ΔMj is is the total mass of sediment retention in each reservoir (T year^{-1}), Vo,j is initial volume of the reservoirs (m^3), ξm is the rate of sediment retention (equal to $3.65.10^{-7}$ T m^{-3} MJ^{-1} mm^{-1} ha h) and Rj is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1}). The rainfall erosivity valid for the Brazilian semiarid region is a function of monthly (Pm) and annual (P) total precipitation (mm).

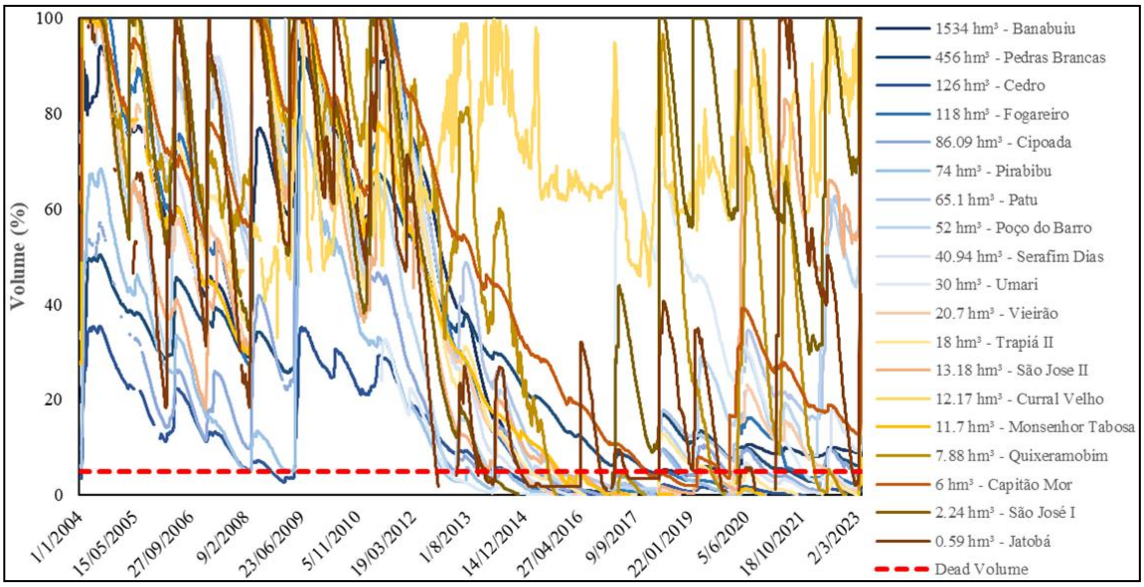
Thus, the total sediment retention for each catchment was the sum of total mass of sediment retention in each reservoir. It's important to highlight that only sediments from non-strategic surface reservoirs with flooded areas larger than 5 hectares were considered. The nutrient content in the sediment was assumed as the mean value of each nutrient (N, P and K) for the sediment samples of our database (see Section 2.2) from the Banabuiú catchment and JRB.

3.3 Results and discussion

3.3.1 Accessibility for sediment extraction in the Banabuiú catchment

The temporal water storage dynamics of the 19 monitored reservoirs in Banabuiú are presented in Fig.2. Note that reservoirs with larger capacities, as Fogareiro and Cipoada, need longer periods of rainfall to reach higher volumes. On the contrary, the smaller ones present a much more intense dynamic of filling and emptying, as for Jatobá and São José I reservoirs. Moreover, extended droughts, such as the period between 2012-2018, can cause alterations in the water balance of small reservoirs, leading to a situation in which they remain empty (or partially empty) during the recharge period (Zhang et al., 2021). Thus, the bottom sediment of these reservoirs is exposed with relatively high frequency and can be removed from the system by excavation, which offers several advantages. Excavation is cheaper and faster compared to other sediment removal techniques - such as dredging - which makes it a more feasible solution for regions with limited resources. In addition, there is no need to dewater the sediment before application on the soil, which also reduces the costs of the sediment reuse technique. Furthermore, according to Moog et al. (2018), although sediment removal by excavation could reduce the biomass of benthic invertebrates by 82%, the fauna in the affected area would return to pre-operation conditions in approximately 235 days, and looking at the Fig 2, it is noticeable that the reservoirs, once they have become empty, take longer than this window time to fill up.

Figure 2 - Temporal water storage dynamics of the monitored reservoirs between 2004 and 2013 in Banabuiú catchment, indicating the frequency with which the reservoirs' sediments are exposed and available for extraction. The line color indicates the reservoir capacity from small (brown) to large (blue).



3.3.2 Spatio-temporal dynamic of sediments

The ANOVA analysis for the different periods of the physicochemical characteristics of the sediments from São Nicolau (Fig. 3) showed that fluctuations from 2016 to 2021 in the reservoir were statistically insignificant (p-value > 0.05), except for Na, C and N. Still, in general, the highest levels were recorded in 2016. On the other hand, for the São Joaquim reservoir, only the K averages showed statistical differences between the years, with higher averages observed in 2021, except at point SJ05 (Fig. 4).

Figure 3 - Spatio-temporal assessment of the physicochemical properties of sediments from São Nicolau reservoir. The values were normalized by the database maximum value to be presented on the same scale. The temporal evolution of the reservoir flooded area is represented at the bottom by Sentinel-2 satellite images in true color.

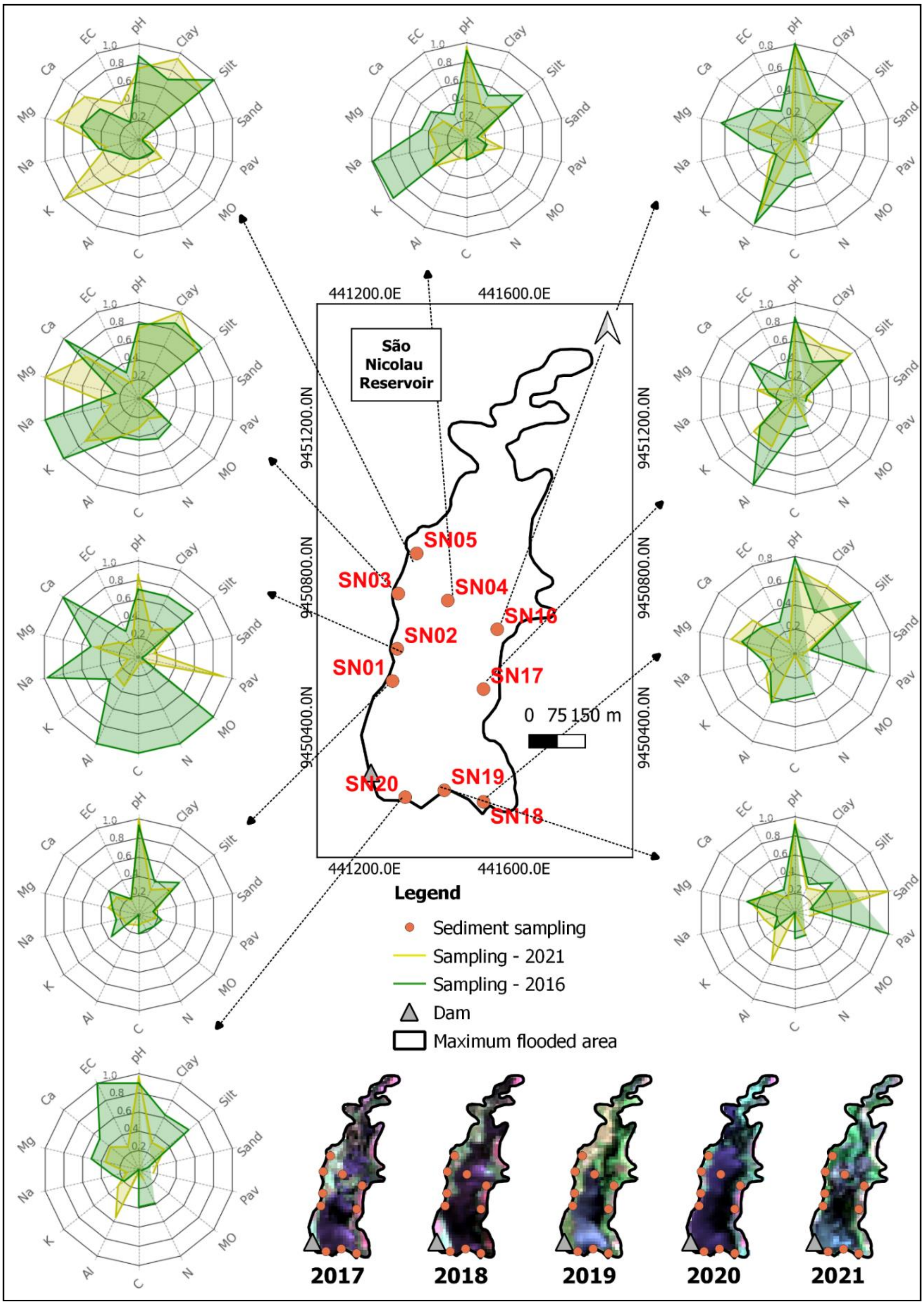
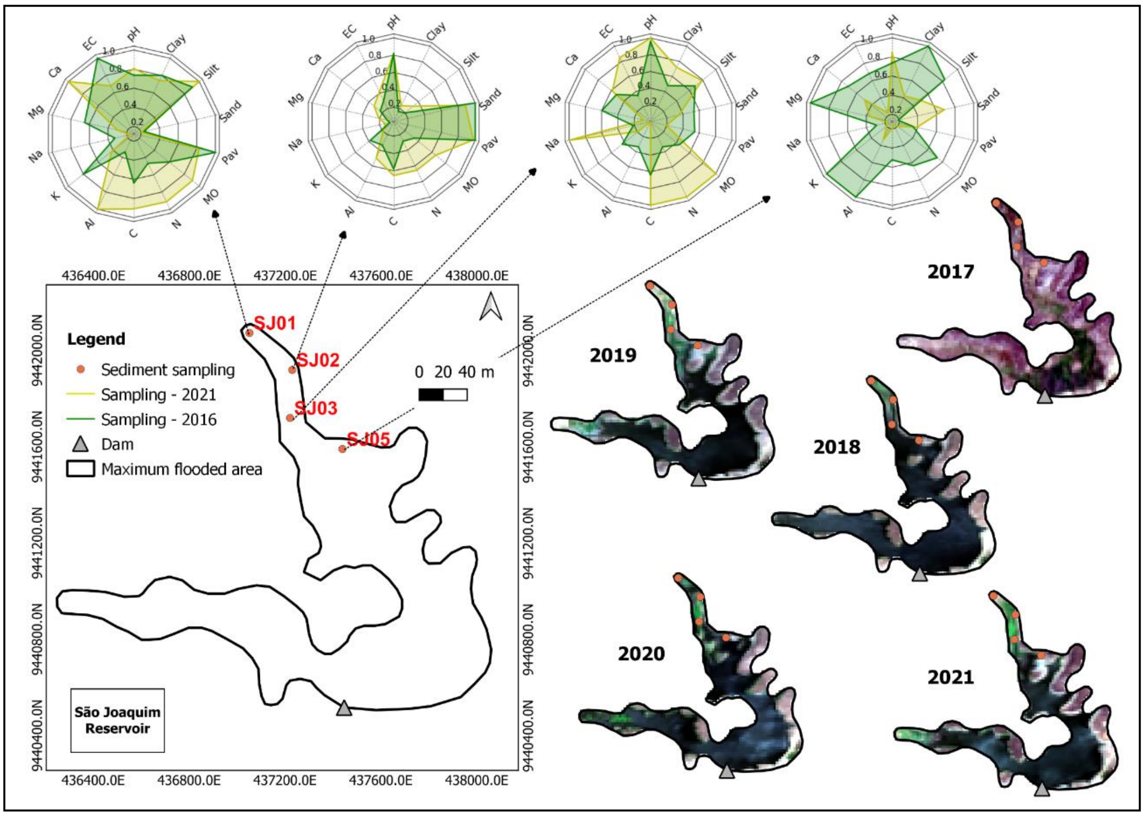


Figure 4 - Spatial-temporal assessment of the physicochemical properties of sediments from São Joaquim reservoir. The values were normalized by the database maximum value to be presented on the same scale. The temporal evolution of the reservoir flooded area volume is also represented at the bottom by Sentinel-2 satellite images in true color.



This result may have been associated with the prolonged drought that the region faced from 2012 to 2017 (Marengo et al., 2017), which led to the accumulation of nutrients in the sediment. However, from 2018 - 2021, rainfall was within the historical average for the region and the reservoirs were partially filled (at the bottom of Fig. 3 and 4 the reservoir flooded area over time is shown). With the increase in the water level, it is likely that nutrients were transferred from the sediment into the water column, which may have caused the decrease of the water quality (see, for instance, Lima Neto et al., 2022). In addition, these nutrients may have been used by aquatic plants for biomass growth (Kalengo et al., 2021) or removed from the system during the water uptake process. On the other hand, since points SN05 e SN03 are further from the dam and located in areas not submerged during the analyzed period, there was an even higher accumulation of nutrients at that area. Some particular circumstances may have caused this result, such as crop cultivation on the reservoir's banks (Fig 5A-B) and livestock farming in the surrounding areas (Marengo et al., 2021), as nutrients from animal waste accumulate in the soil can be transported by surface water into water bodies. In the São Nicolau reservoir, one of the water uses is for watering livestock (Fig. 5C-D). According to Leip et al.

(2015), among the anthropogenic factors responsible for supplying nutrients to surface waters, livestock farming is one of the most important sources. We also assume that the analyzed time window (5 years) is not enough to detect large changes in the physicochemical properties of the sediments. Ebrahimi et al. (2023) also did not observe significant changes in phosphorus concentrations for the different four seasons in the sediments of the southern Caspian Sea.

Figure 5 - Bean (A) and grass (B) cultivation near the sediment sampling points in the São Joaquim reservoir. In C and D, livestock farming on the banks of the São Nicolau reservoir. Cattle also usually access the lake directly for drinking.

3.3.3 Economic analysis of the sediment reuse practice

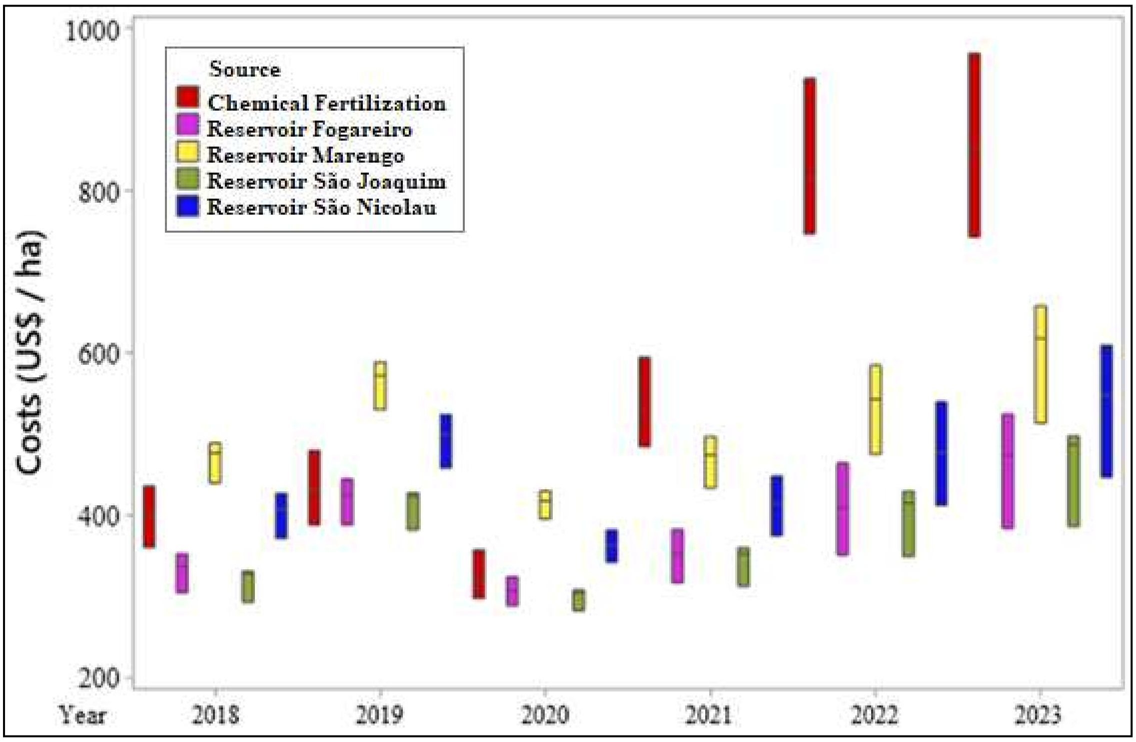
There are various technical solutions available to control the increasing use of chemical fertilizers, such as crop rotation or intercropping, organic-inorganic compound fertilizers, organic fertilizers, and recycled agriculture (Wang et al., 2018). Also, dietary changes and higher consumer demand for organic food may affect the use of chemical fertilizers (Nikaflar et al., 2023). In this context, sediments can serve as a soil conditioner, increasing agricultural production while contributing to environmental sustainability (Mattei et al., 2017;

Kiani et al., 2021, Braga et al., 2023) in an economically feasible way (Braga et al., 2019; Nikaflar et al., 2023).

Nikaflar et al. (2023) have verified that replacing chemical sources of the macronutrients N, P, and K by sediments from Latian Dam, Iran can generate a potential profit of more than $68 million per year. In our previous study (Braga et al., 2019), we observed that the application of sediment to the soil in our study area could lead to savings related to soil fertilization of up to 29%, while in reservoirs with low nutrient content in the sediment, the practice could increase the costs compared to traditional fertilization.

However, fertilization costs are time variable, for example, due to changes in the global food market (Hassen and Bilali, 2022) and/or availability of chemical fertilizers, whereas the costs with sediment reuse tend to be more stable. Fig. 6 presents the results of the cost-benefit analysis for soil fertilization over the period 2018-2023. With the inclusion of the environmental permit costs for reservoir desilting (a mandatory step in the study region) to the values calculated by Braga et al. (2019), the sediment reuse costs, except for Marengo reservoir, become of the same order of magnitude as traditional fertilization between 2019 and 2020 (Fig 4). Note that indirect benefits related to the recovery of the reservoir's storage capacity and improvement of water quality (with reduced costs for water treatment) are not even being considered in this analysis. However, since 2021, the costs of conventional fertilization have increased markedly and these increases are far more significant than the increase in the factors that compound the sediment reuse cost. Among chemical fertilizers, K has the highest variation, being up to 316% higher now than in 2018 (Table 2). Thus, using sediment as a nutrient source in agriculture reduces the costs in all scenarios and enhances the predictability of agricultural production.

Figure 6 - Temporal variation (2018-2023) of the costs of conventional soil fertilization and sediment reuse to meet the nutritional requirement of maize. FO, MA, SN and SJ refer to the sediments from Fogareiro, Marengo, São Nicolau and São Joaquim reservoirs, respectively. CF means conventional fertilization. All values obtained in Brazilian Reais were converted to US dollars adopting an exchange rate of 3.83, 3.94, 5.15, 5.39, 5.16, 5.10 R$/US$, from 2018 to 2023, respectively.



In the specific period assessed by us (2018-2023), the COVID-19 pandemic and the war in Ukraine have disrupted several supply chains and logistics worldwide, affecting the prices of fertilizer (Rice et al., 2022). According to Wang et al. (2018), the supply-demand balance, weather conditions, production costs and trade flows are some factors that influence the fertilizer market. It is important to note that the supply of mineral fertilizers is geographically concentrated and controlled by a small number of companies and countries (Hassen and Bilali, 2022). For example, Russia and Belarus account for 1/3 of potash fertilizer exports worldwide, thus defining its price (Benton et al., 2022). Besides, Russia is still currently the world's leading exporter of nitrogen fertilizers. The production of these fertilizers is based on the use of natural gas as a raw material, whose price rose significantly in 2021, when nitrogen fertilizer prices have reached their highest level since 2010. Regarding phosphorus-based fertilizers, the price has also been affected by export restrictions resulting from domestic trade policy measures, such as in China, which is a major producer and supplier of phosphate fertilizers, but between July 2021 and June 2022 chose to limit its exports in order to secure domestic supplies (Benton et al., 2022).

To understand the overall impact of fertilizer prices on global food security, it is mandatory to acknowledge the long-term and large-scale side effects of these conflicts, especially in developing countries where a sharp increase in fertilizer prices can preclude their use and reduce crop productivity (Hassen and Bilali, 2022). An example of side effects of the recent crisis was observed in Brazil: one of the alternatives proposed was to open potash mining areas on indigenous lands, under the justification of the country's prominent position as the second largest consumer of potassium in the world (Clavery and Barbiéri, 2022). In this context, new sources of nutrients to plant farming can be a potential alternative to guarantee agricultural productivity, especially for small farmers, who are financially more vulnerable.

3.3.4 Legislation on sediment reuse in agriculture

This analysis included the following issues: existing relevant legislation in Brazil (Section 3.4.1) as well as other parts of the world (Section 3.4.2) and suggested steps for regulating the reuse of sediments for agricultural purposes (Section 3.4.3).

3.3.4.1 Existing relevant legislation in Brazil

The reuse of sediments is one of the most promising alternatives to chemical fertilizers (Baran et al., 2019a) due to technical (improving soil quality), economical (can decrease the agricultural production costs) and ecological (nutrients recycling) reasons. However, sediments are slightly heterogeneous and may contain some elements, such as heavy metals, organic contaminants and pesticides (Canet et al., 2003), that could limit their use in agriculture. The land use, from which the sediment originated, and possible remediation methodologies applied are factors that determine the presence or absence of these contaminants, as well as their content(s) (Macci et al., 2022).

Sediments from shallow lakes and surface reservoirs, located far from large urban centers, are generally considered to be low-risk sources of heavy metals and other contaminants, due to the fact that these water bodies typically receive relatively little input from anthropogenic sources, such as domestic and industrial wastewater. Furthermore, sediments in these environments tend to be relatively young, with low residence time of the water (around 2 years), meaning that the possible contaminants that do enter the system are unlikely to accumulate to high levels over time (Moura et al., 2020). Therefore, sediments extracted from such water bodies may not require the same level of analysis as those from other environments.

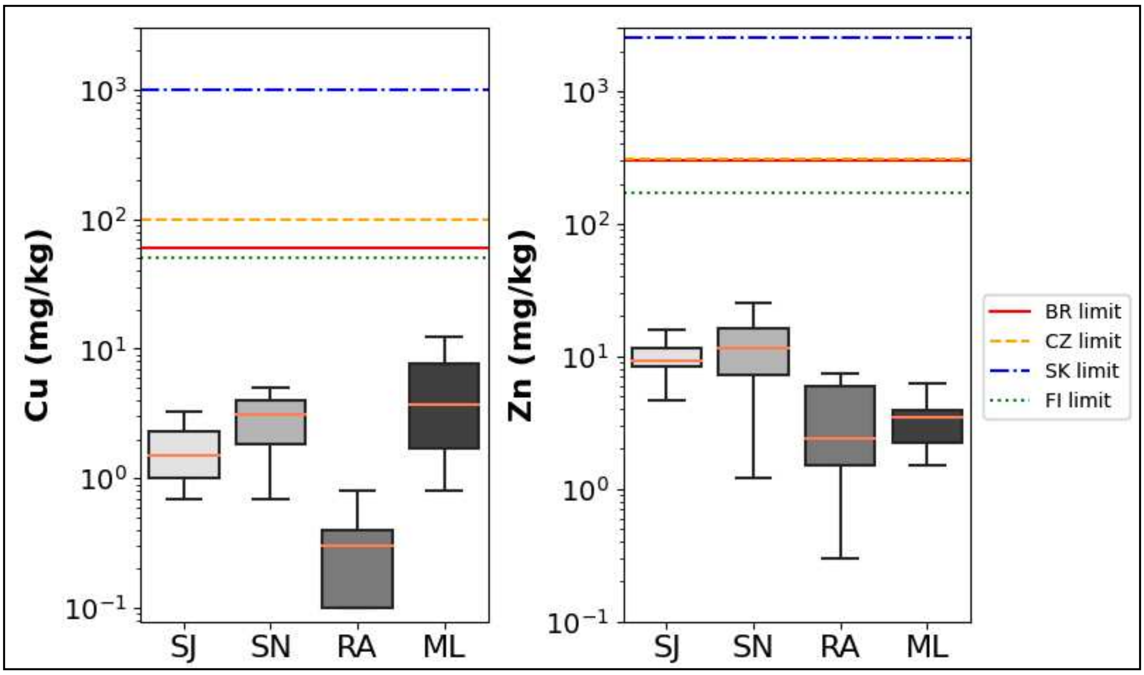
In this context, one possibility to assess the safety of using sediment for agricultural purposes is the maximum limits of contaminants allowed in fertilizers and/or agronomic substrate for plants, established by the Brazilian Secretary of Agriculture (BRAZIL, 2016). However, our database does not include the contaminants presented in this regulation (arsenic, cadmium, lead, mercury, chromium, nickel and selenium). Also, the Brazilian National Environment Council, through Resolution n° 454/2012, established guidelines and procedures for the management of sediments from water bodies under national jurisdiction (CONAMA, 2012). The regulation indicates the disposal of dredged sediments on soils for agricultural purposes as a possibility of beneficial use of the material, depending on the analysis of economic-environmental feasibility and its classification. According to the legislation, the dredged material (when disposed of in soil) must present lower concentrations than the alert limits established for soils (CONAMA 420/2009). Thus, it is suggested that only sediments within this class should be considered to be re-used as a nutrients source for plants. The sediments assessed in our study presented trace element contents markedly lower than the alert limits (Fig 7), indicating that, despite the heterogeneity of the sediment, its use for agricultural purposes should be safe.

Therefore, whereas sediment sampling from the Brazilian semiarid region may not be mandatory to detect trace elements contamination, it is still an important tool for assessing overall sediment quality and identifying potential limitations of its reuse for agriculture. In addition to the content of trace elements in the sediment, the application of sediment may increase their concentrations in plants (Baran et al., 2019a; Szara-Bąk et al., 2023; Tarnawaski et al., 2015), depending on the type and dose of sediment applied (Kazberuk et al., 2021). The Brazilian legislation also establishes Maximum Limits for Inorganic Contaminants in Foods (BRASIL, 2013). However, for maize, only values for arsenic, lead, and cadmium have been defined, which are elements not analyzed in our study.

3.3.4.2 Existing relevant legislation in other countries

Currently, the reuse of sediments in agriculture has gained significance, since numerous countries are searching for alternative sources of nutrients, less dependent on the fertilizer market and with lower environmental impacts (ESPP, 2023). The accessibility of these sediments as fertilizers could be a key factor in addressing the issue of global food security (Szara-Bąk et al., 2023). The analyses of the Copper and Zinc concentration from the studied reservoirs showed that the concentrations of these elements in the sediment are well below the maximum limits allowed by the existing legislations for the direct reuse of sediment in agriculture in other countries (Fig 7). The highest concentrations of zinc and copper were 12.1 and 4.8 mg/kg, respectively. However, these concentrations are 4 and 35 times lower than the limits set by the most restrictive legislation (Finland regulations) for copper and zinc, respectively.

Figure 7 - Copper (Cu) and Zinc (Zn) concentrations in the sediments from Raiz (RA) and Mel (ML) reservoirs. The lines represent the limits established for the disposal of sediments in soil by Brazilian legislation (BR) and direct reuse in agriculture by Slovakian (SK), Czech (CZ) and Finnish (FI) regulations.



Szara-Bąk et al. (2023) observed similar results to the content of copper and zinc for bottom sediments from Rożnów reservoir. Macci et al. (2022) also observed concentrations of zinc and copper within these limits to saline-remediated and brackish sediments. Baran et al. (2019a), working with bottom sediments from a reservoir located in an urban development area in Poland to water intake mostly, have observed the exceeding of these elements concentrations as well. However, Nin et al. (2022) working with treated sediment from an urban port, and Leue and Lang (2012) with sediments from an urban channel, have found high concentrations of heavy metals. Besides the limits shown, in Sweden, the ratio between cadmium and phosphorus content is the parameter of regulations governing the possible use of sediments in agriculture

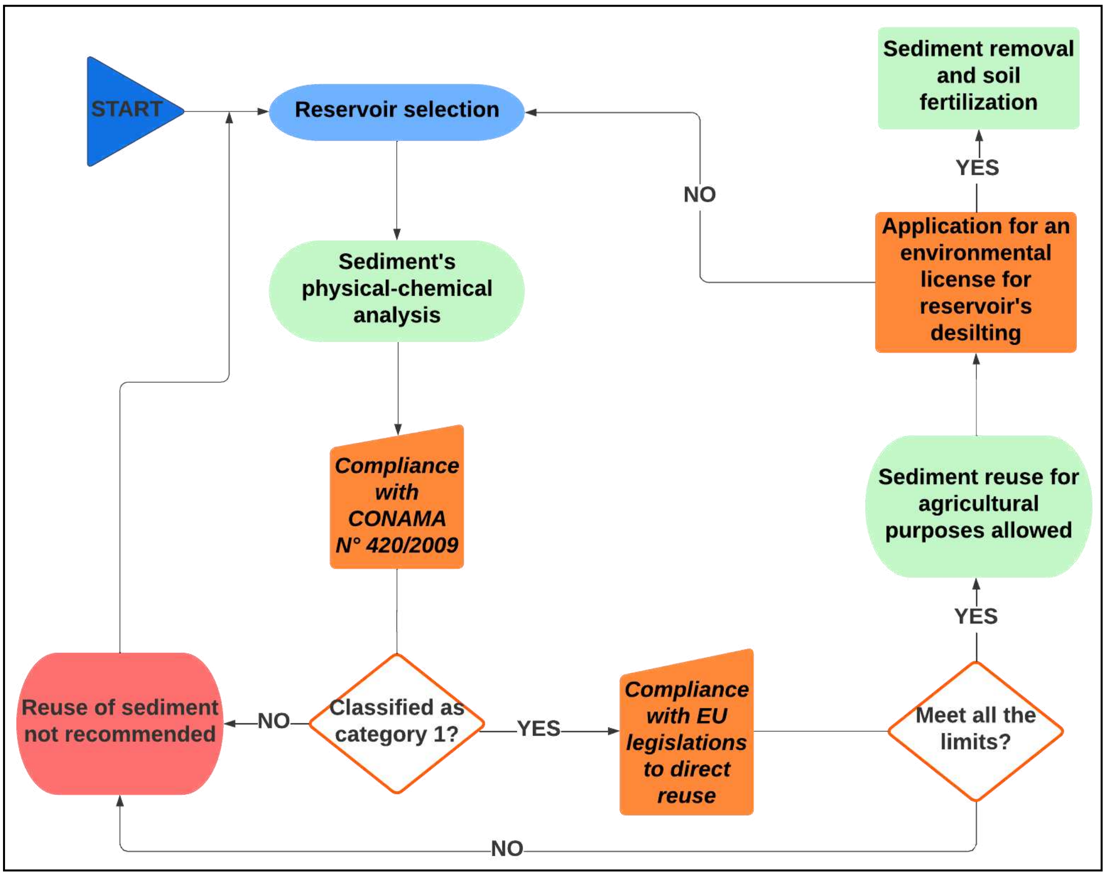
(Djerf and Ferrans 2022). In Poland, the reuse of sediments is only legally possible if it is proven that the sediments are classified as non-hazardous (EU, 2008).

3.3.5 Suggested steps for regulating the reuse of sediments for agricultural purposes

In order to ensure safe and responsible use of sediment as a nutrient source for plants, as an alternative or a complement to chemical fertilizers, it is important to develop regulations with specific guidelines for its use in agriculture. Promoting the application of uncontaminated dredged sediment contributes to avoid dismissing the material, as happened in the new EU regulations on fertilizers (Renella, 2021). These regulations should also set procedures for monitoring the practice to ensure compliance with environmental standards, therefore policymakers can promote the safe and sustainable reuse of sediments as a valuable resource for agricultural production, contributing to a circular economy (Brils et al., 2014).

Other already existing legislation should also be considered for the regulation of sediment reuse in Brazil: the environmental permitting for reservoirs' desilting. This law is related to the final step of removing the sediment from reservoirs' bed, which will depend mainly on the characteristics of the water body (for instance, if the desilting area is less than a hectare, only a simplified environmental permitting process is required). The full compliance with all the legislations mentioned could serve as a starting point for regulating sediment reuse in Brazil, thereby ensuring its safe and sustainable utilization by the agricultural sector (Fig 8).

Figure 8 - Suggested steps for regulating the reuse of sediments for agricultural purposes in Brazil. Category 1 (CONAMA 420/2019): soils (sediments in this case) with contents of chemical elements lower or equal to the reference values.

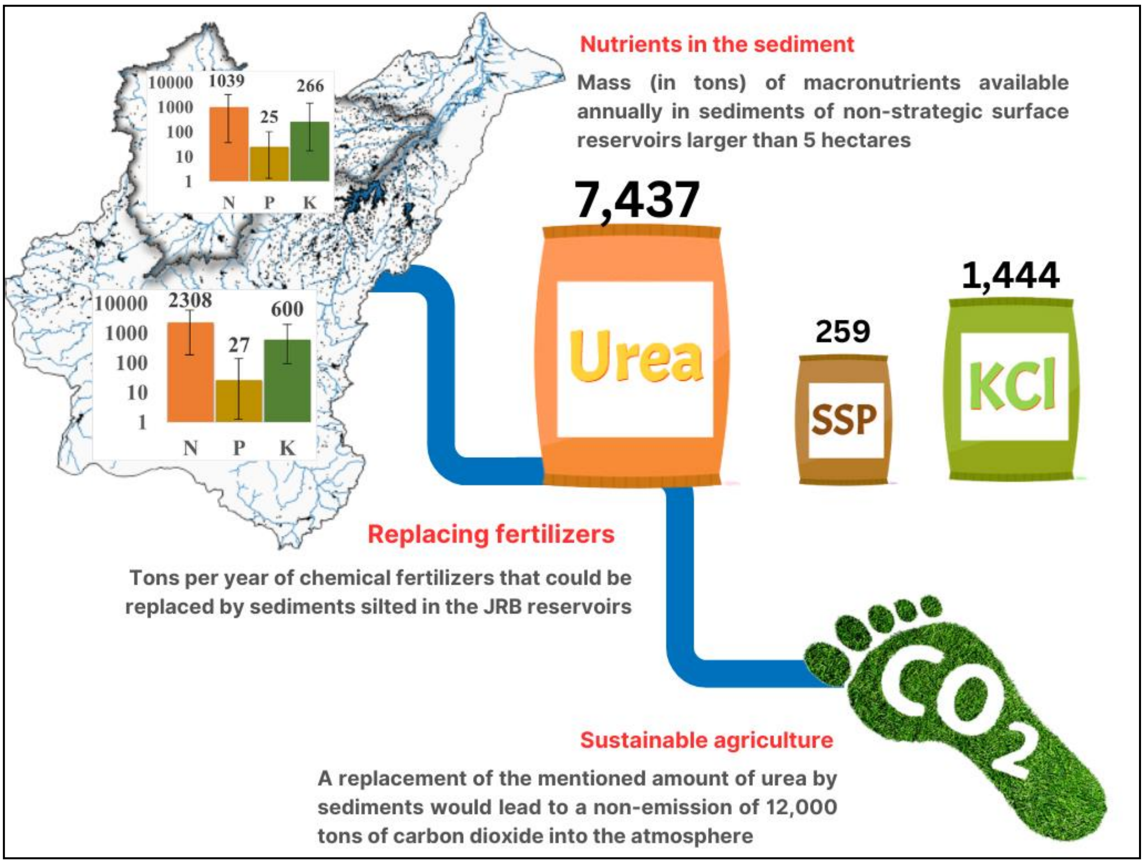


3.3.6 Sediment reuse in agriculture: a more sustainable crop production

The main benefit of reusing sediments for soil fertilization is to decrease the use of chemical fertilizers by the application of the model proposed by Lima Neto et al. (2011), we estimated that, in the Jaguaribe River Basin, approximately 2 x 10^6 Tons of sediment are deposited annually in the almost three thousand non-strategic surface reservoirs larger than 5 ha.

In our previous study (Braga et al., 2023), we reported the variability of macronutrient content in the sediments of the reservoirs studied in the JRB and the Banabuiu sub-basin. Considering the average content of nutrients in sediments and the rate of sediment deposition in these water bodies, we estimated the mass of available NPK. Sediments from the Banabuiu catchment accumulate 1039 tons of nitrogen, 25 tons of phosphorus, and 266 tons of potassium per year, approximately (Fig 9). Scaling those values up to the Jaguaribe River Basin, despite the slightly lower nutrient concentration in the sediment of the reservoirs in this larger area, we estimate approximately 3347, 52 and 867 tons of nitrogen, phosphorus and potassium, respectively. By applying this approach, we assumed that the nutrient content in the sediment is temporally constant, but in the same study we recognized that there is a temporal variation in the physicochemical properties of the sediment. However, since it was not possible to set a clear temporal pattern for the macronutrients in the sediment (at least for the time window analyzed in this study), we adopted a constant mean value for the JRB and the Banabuiu sub-basin, which may represent a shortcoming of our estimation. Among the macronutrients, nitrogen shows the highest amount in the sediments. When compared to chemical fertilizers, this result means that the sediments deposited in surface reservoirs in the JRB could replace almost 7437 tons of urea (45 % of N), 259 tons of simple superphosphate (20% of P) and 1444 tons of potassium chloride (60 % of K).

Figure 9 - Amount (ton year^{-1}) of nutrients potentially provided by the sediment from non-strategic reservoirs (larger than 5 ha) in the Banabuiu sub-basin and the Jaguaribe River Basin.



The partial replacement of chemical fertilizers by sediment reuse has potential to reduce the carbon footprint of the agricultural sector. For instance, the chemical N fertilizer supply chain has released into the atmosphere 1129.1±171.1 M tons CO$_2$e in 2018 (Menegat, Ledo and Tirado, 2022). This value consists of the GHGs emissions of manufacturing, transporting and subsequent direct and indirect soil emissions of the fertilizer application on agricultural lands. The production and transportation are responsible for 41.4% (0.48 G tons CO_2e) of global GHG emissions from synthetic N fertilizers. Furthermore, according to Bentrup et al. (2018), for the year 2014, the reference value for urea carbon footprint in Latin America was 1.7 tons CO_2e per tons of product. Therefore, the replacement of chemical nitrogen fertilizers by sediments in the JRB could lead to a decrease of almost 12 x 10^3 tons CO_2e being released into the atmosphere. This benefit can be even more significant, as the sediments also contain other macronutrients, resulting in a reduction of the carbon footprint associated with replacing phosphorus (P) and potassium (K) inputs in agriculture as well. Although the sediment reuse technique may involve some CO_2 emissions due to the transport and excavation from reservoirs' bed, these emissions should be considerably lower when compared to chemical fertilizers.

3.3.7 From science to practice

The use of mobile technologies has the potential to transform the entire industry, including agriculture (Masuka et al., 2016). Communication and access to information in rural areas had long been limited, due to factors such as the lack of a telephone network, resources to purchase digital devices and good quality internet networks. However, the advances in communication technologies and universal access to the internet have allowed these areas to connect to others locally, regionally and internationally. The democratization of access to internet and mobile devices was mainly due to the significant decrease in the costs of these technologies, enhancing accessibility. In spite of the deep social inequalities in Brazil, it is considered as one of the nations to adopt, in a more intense way, new technologies and digital culture (Pellanda, 2010).

According to the Brazilian Telecommunications Agency (ANATEL, 2020), about 97% of the population has access to mobile telephony, with higher percentages in the South, Southeast and the Federal District regions. In the agricultural sector, mobile devices have helped to disseminate knowledge and high-quality information globally among rural producers, institutions and suppliers (Bambini, Luchiari-júnior and Romani, 2014). Mobile information and communication technologies can also increase productivity among small farmers (Nyamba and Mlozi, 2012), for instance, with updates on weather forecast, climate change and the agricultural market, enabling them to make more assertive decisions (Masuka et al., 2016).

A number of large companies, individual microentrepreneurs and government agencies are developing applications to support farmers and other stakeholders (Roberts and Mcintosh, 2012). In our study, we developed a platform to integrate our findings on sediment reuse, RESED, available at https://resed-cientista-chefe-v1.streamlit.app/. With RESED, users can use their own soil and sediment data to easily calculate the mass of sediment needed to fertilize the soil, as to meet the demands of the selected crop, and confirm if the practice is economically feasible in that specific situation. The tool is expected to disseminate the sediment reuse practice for agricultural production by small farmers in the study region.

3.4 Conclusion

The reuse of sediments from reservoirs' beds in agriculture can increase crop yields and has substantial benefits for the environment and society. However, the study showed that spatio-temporal variability of the physico-chemical characteristics of the sediment may be an obstacle to disseminate the practice. The high concentration of nutrients such as K, Ca and Mg, and mainly P in the sediment reveals the feasibility of its use as a source of nutrients for crop production, while closing the cycle of phosphorus in agriculture. The water storage dynamics in the reservoirs of the study area expose the sediment frequently and for long time periods, making them easily available by excavation. These two conditions increase the feasibility of sediment reuse in semiarid regions. Moreover, the analysis of heavy metals and trace elements in the sediment showed that the material is not contaminated, decreasing the risk of negative environmental impacts of the practice. However, in Brazil, it is necessary to establish guidelines and regulations in order to ensure that the sediments are reused in the best and safest way. By 2020, the cost of sediment reuse was about the same order of magnitude as traditional fertilization. However, the prices of chemical fertilizer can vary considerably, especially during global crises, when sediment reuse becomes even more attractive, since sediment reuse costs are more stable, thus providing predictability to the agricultural sector. Currently, sediment reuse can lead to savings of up to 68% when compared to traditional fertilization in the study region.

As a perspective to implement the practice in the semiarid area of Brazil, we developed a public access platform with our research findings, bringing science and society closer together. As the next step of this research, it is our goal to map the nutrient content of soils and sediments on a regional-scale using hyperspectral satellite imagery, to identify potential reservoirs with sediments suitable for agricultural reuse, as well as nutrient-deficient soils. Finally, we propose further research on other benefits of sediment reuse practice not assessed in this study, such as the impact on carbon footprint by replacing chemical fertilizers, the potential benefits in the water retention capacity of soils and water quality alterations by removing the nutrient-enriched sediments.

4 CHAPTER III - MAPPING PHYSICOCHEMICAL PROPERTIES OF SOILS AND RESERVOIRS SEDIMENTS FROM THE BRAZILIAN SEMIARID REGION BY MULTI- AND HYPERSPECTRAL DATA

Abstract: To effectively integrate sediment reuse in agriculture, comprehensive knowledge of the physicochemical parameters of sediment on a large spatial scale is essential. An alternative approach for indirect analysis of soil and sediment attributes is the use of VNIR-SWIR spectroscopy. This study aims to explore the connection between spectral indices and soil properties (salinity, clay content, and organic carbon), model these parameters using the PLSR method based on spectra and compare the accuracy of selected indices and models to various satellites (Sentinel, PRISMA, and EnMAP) in soil property estimation. The study was carried out using bare soil reflectance data of topsoil data collected in Northeast Brazil and bottom sediment collected from a shallow reservoir. Pre-processing techniques were employed, including first-derivative spectra smoothened using the Savitzky–Golay technique and continuum-removal. The approaches were also tested for different dataset combinations (only soil, only sediment, soil-sediment database). The combination of reflectance spectroscopy with multivariate statistical techniques seems to be an effective approach for predicting electrical conductivity, organic carbon and clay content of soils and reservoir sediments in semi-arid regions. Better accuracy can be achieved if models are built for each environmental component individually. The prediction of salinity in both soil and sediment samples was most accurate using the ratio index (RI) model combined with the FD-SG preprocessing. On the other hand, PLSR models seem to be more suitable for predicting soil organic carbon and clay content, especially when no pre-processing of the spectrum is used.

Keywords: sediment reuse; soil spectroscopy; spectral indices; multivariate statistical techniques; soil property estimation

4.1 Introduction

Sediment reuse has emerged as a promising alternative to chemical fertilizers in subsistence farming, due to its high concentration of nutrients and organic matter (Canet et al. 2003; Tarnawski et al. 2015; Renella 2021; Kiani et al. 2021). In addition, the higher fine particle content of the material in relation to soil, not only improves the physical structure of the soil, but also significantly increases the water retention capacity of the substrate (Brigham et al. 2021). Furthermore, the environmental benefits associated with this practice include the reduction of the carbon footprint in agriculture, due to the non-use of chemical fertilizers, and the promotion of the closure of the phosphorus cycle in agricultural production (Braga et al. 2024). The use of sediments as soil conditioner presents itself as an economically feasible technique, being a sustainable option for agricultural fertilization (Braga et al. 2019; Nikaflar et al. 2023).

Hence, in order to establish and integrate the sediment reuse practice within the agricultural production system as a crucial approach for soil and water conservation, a physicochemical sediment characterization at the reservoir scale is essential. However, a very significant spatial variability of soil and sediment properties have already been demonstrated in the literature (Braga et al. 2023, Braga et al. 2019). Even though physicochemical laboratory analyses are essential for agricultural planning, it has several disadvantages such as they are a time-consuming and costly process, especially at the reservoir scale. Additionally, in the Banabuiú River Basin, the study area of this work and situated in the northeast region of Brazil, has a dense reservoir network, with more than 1,000 reservoirs with surface areas larger than 5 hectares in the basin (Pekel et al. 2016), usually built by the community itself, in the search for adaptation to prolonged droughts, serving as the primary water sources for meeting the local population's demands (Pereira et al. 2019). In this scenario, satellite imagery presents a significant advantage for monitoring soil properties at both field and regional scales.

Therefore, an alternative approach for indirect analysis of soil and sediment attributes is the use of visible near-infrared and short-wave infrared (VNIR-SWIR) spectroscopy. This method offers a faster and more cost-effective solution compared to traditional laboratory procedures, while also allowing for repeatability and reproducibility at various temporal and spatial scales (Carvalho et al. 2022). The relationship between soil components and the electromagnetic spectrum has facilitated the development of soil spectroscopy techniques that can estimate soil properties in the laboratory and increasingly from airborne and satellite platforms (Chabrillat et al. 2019, Ben-Dor et al. 2018). For instance, clay minerals exhibit distinctive spectral features in the shortwave infrared region (SWIR) between 2170 and 2360 nm (Mzid et al. 2022). Similarly, gypsum exhibit absorption bands at 1800 nm and 2300 nm (Moreira et al. 2014) and soil organic carbon (SOC) significantly influences the shape and nature of soil reflectance spectra (Gomez et al. 2008), displaying specific features in the visible region at around 664 nm and in the SWIR region due to organic compounds such as lignin and cellulose (Viscarra Rossel et al. 2019, Liu et al. 2019). Additionally, the biochemical components of soil organic matter affect reflectance in the visible (400–700 nm) and NIR-SWIR (700–2500 nm) intervals of the spectrum (Ward et al. 2020).

Multispectral satellites, like Sentinel-2, have showcased their potential for identifying bare soil areas in agricultural regions and subsequently monitoring soil characteristics across extensive territories (Wang et al. 2019). Their short revisit intervals and a moderate spatial resolution offer several advantages, increasing the likelihood of capturing cloud-free images, a critical aspect in soil imaging spectroscopy given the limited timeframe for observing bare soil on agricultural land. Nevertheless, the precise prediction of soil parameters using multispectral imagery has been hindered by inadequate spectral resolution (Castaldi et al. 2019), primarily due to the absence of narrow bands in the shortwave infrared (SWIR) region, which is significantly influenced by soil chromophores. In this regard, hyperspectral remote sensing emerges as a suitable technology for creating highly accurate topsoil maps (Paz-Kagan et al. 2015). Hyperspectral satellites with a sufficient signal-to-noise ratio (SNR), such as PRISMA (Loizzo et al. 2019) and EnMAP (Guanter et al 2015), enable more precise soil parameter predictions compared to current multispectral sensors. The literature contains numerous articles discussing the estimation of soil variables by leveraging satellite hyperspectral data, often resampled or simulated through statistical models (Rocha Neto et al. 2017, Mzid et al. 2022).

Due to the extensive nature of hyperspectral data, the presence of faint spectral features overlapping with the fundamental vibrational band can pose challenges in direct interpretation. Therefore, a range of calibration techniques is employed to establish the connection between spectral data and soil properties. Among these techniques, Multiple Linear Regression (MLR), Principal Component Regression (PCR), and Partial Least Squares Regression (PLSR) are the most commonly employed methods (Rocha Neto et al. 2017). When it comes to quantitatively predicting soil chemical properties, PLSR has proven to be the most effective multivariate approach for estimating soil parameters such as carbon (Ward et al. 2020) and organic matter content (Angelopoulou et al 2023), soil nitrogen content (Jiang et al. 2017), as well as micronutrients like copper and iron (Jiang et al. 2020).

The characterization of sediment becomes particularly viable in semiarid regions characterized by flood-drought dynamics (Medeiros and Sivapalan, 2020). In the specific context of Northeast Brazil, where this study was conducted, small and medium-sized reservoirs frequently dry up during the intra-annual dry season, revealing the accumulated sediment and making it readily accessible. This favorable condition enhances the opportunities for periodic sampling and analysis of the sediment, including the utilization of multi and hyperspectral imagery. As a result, when the sediment proves to be efficient for soil fertilization, it can be easily excavated and reused. In this scenario, the objective of this study is to (1) investigate the relation between spectral indices based on reflectance features of biochemical constituents and the soils' salinity, clay content and organic carbon, (2) model and estimate these parameters using linear (PLSR) method based on the spectra, (3) apply these methods to different satellites (Sentinel, PRISMA and EnMAP) and (4) compare the accuracy of selected indices and models for estimating soil properties.

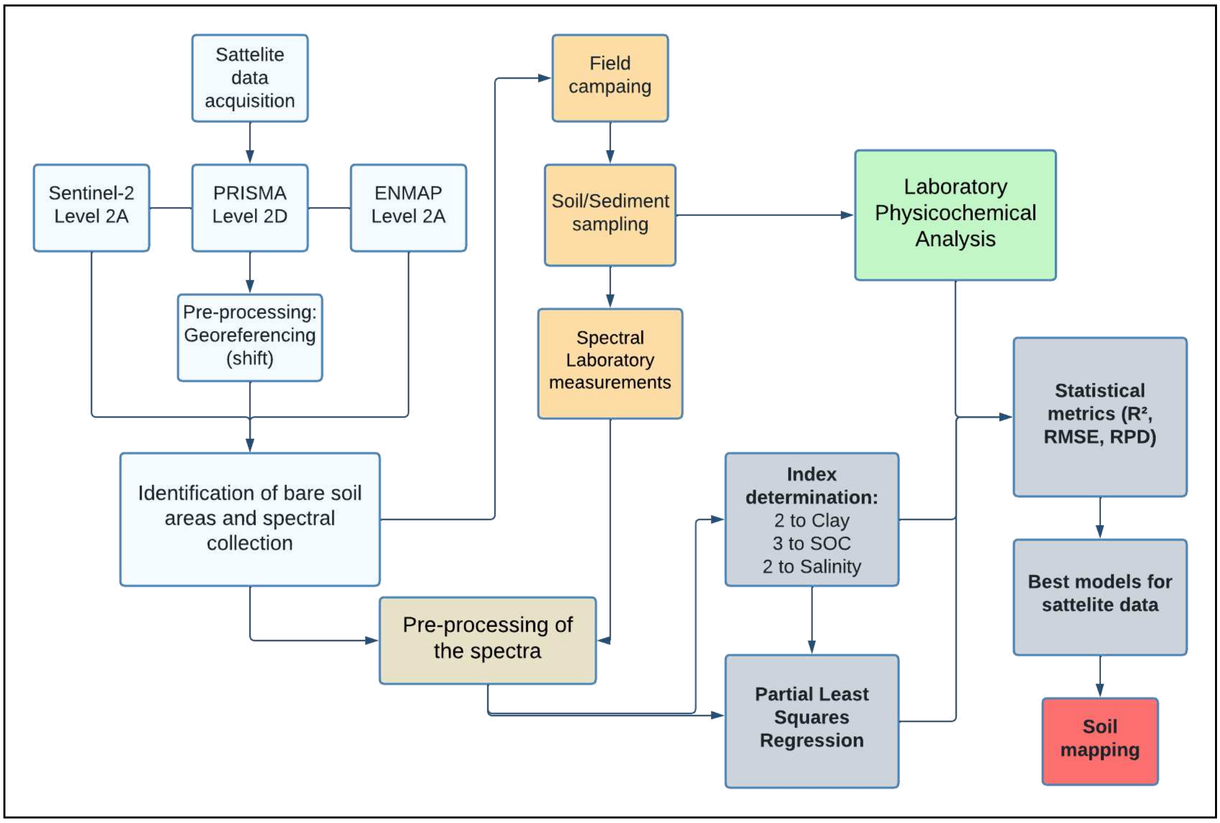
4.2 Study area

The Banabuiú River Basin covers an extensive area of approximately 19,800 km². The Basin is composed of planosols, neosols, organosols, argisols, and luvissols; and geologically, is characterized by a crystalline basement, with limited and spatially heterogeneous groundwater availability. The region's climate is defined, according to the Koppen classification, as hot tropical semi-arid climate, with an average precipitation of 750 $mm.ano^{-1}$. However, the potential evaporation rates can soar up to 2500 mm annually, in addition a concentrated rainy season between February and May, corresponding to 75% of the annual precipitation (COGERH 2009). Thus, the rivers in this area are intermittent, and the availability of groundwater is limited and spatially heterogeneous, leading to water scarcity issues. This area is home to a population exceeding 500,000 inhabitants, with nearly 70% residing in rural areas. The economy of the agricultural sector in this region is based mainly on livestock farming, including cattle, goats, and sheep, as well as small-scale farming, focusing on crops such as maize and beans (Magalhães et al. 2021).

4.3 Material and methods

The flowchart of the methodology is illustrated in Figure 1 and hereafter, the following steps are described. These include: (A) satellite data acquisition and bare soil identification, (B) field campaign for soil and sediment sampling and analysis, (C) description of the soil and sediment database, (D) spectral laboratory measurements, (E) spectra pre-processing, (F) indexes and linear model application for the prediction of soil and sediments properties based on bare soil spectra from both laboratory data and satellite data.

Figure 1 - Flowchart of the proposed methodology.



4.3.1 Satellite data acquisition

4.3.1.1 EnMAP

The Environmental Mapping and Analysis Program (EnMAP) is an advanced imaging spectroscopy remote sensing mission. Its primary objective is to measure, derive, and analyze both qualitative and quantitative surface variables that capture essential Earth processes, which can be consistently obtained on a global scale (Guanter et al., 2015). To meet specific user demands, the mission offers high-quality data with a swath width of 30 km and a swath length of up to 5550 km per day. The data is characterized by 30 m x 30 m spatial resolution and comprises 224 bands spanning the spectral range from 418.2 nm to 2445.5 nm. These measurements are acquired using a push-broom dual-spectrometer based on a prism. Furthermore, the satellite's unique tilting capabilities of ±30°, coupled with its Sun-synchronous repeat orbit of 27 days, allow for a revisit frequency of less than 4 days. EnMAP's satellite was successfully launched on April 1st, 2022, and is expected to remain operational for over five years. The mission's primary instrument is the Hyper-Spectral Imager (HSI, Kaufmann et al., 2016), which is a push-broom sensor featuring a dual-spectrometer with separate VNIR and SWIR sensors. The VNIR spectrometer covers the spectral range from 418.2 nm to 993.0 nm and is divided into 91 bands with a spectral sampling distance ranging from 4.7 nm to 8.2 nm, averaging about 6.4 nm per band. Meanwhile, the SWIR spectrometer spans from 902.2 nm to 2445.5 nm, consisting of 155 bands with a spectral sampling distance ranging from 7.5 nm to 12.0 nm, averaging approximately 10.0 nm per band. Of these, only 133 bands are transmitted to avoid the spectral regions with strong atmospheric absorption (Storch et al, 2023).

For the study area, two partially cloud-free ENMAP scene were obtained on December 4th and December 8th of 2022, respectively. The images were obtained to a Level 2A, which means a product atmospheric corrected, produces reflectance values for land and water areas and generates several quality masks. Before pré-processing the reflectance spectra from the images, the following bands for the wavelengths: 750-778, 813, 890-958, 951, 962, 973, 1099-1159, 1315-1458, 1900-1960 and ≥ 2350 nm, were excluded due to factors like water vapor, noise, and detector overlap, by visually comparing the soil ground reflectance spectra obtained nearly simultaneously using the ASD FieldSpec Pro spectroradiometer.

4.3.1.2 PRISMA

The Italian Space Agency (ASI) launched the PRISMA hyperspectral satellite system on March 22, 2019. This satellite orbits Earth at a low altitude of 615 km in a sun-synchronous pattern, with a 29-day repeating cycle and the ability to revisit specific targets within a week using off-nadir viewing. Classified as a small satellite, PRISMA has an estimated operational lifespan of 5 years (Cogliati et al. 2021). The instrumentation consists of two hyperspectral sensors and a panchromatic camera. These sensors cover a continuum of 239 spectral bands ranging from 400 to 2500 nm, with 66 bands in the visible-near-infrared (VIS-NIR) range and 173 in the shortwave infrared (SWIR) range. The spectral resolution is below

12 nm, and the spatial resolution is 30 m. The panchromatic camera provides a ground sample distance of 5 m and operates in the 400–700 nm spectral range. Observations were recorded within an area spanning from 180°W to 180°E longitude and 70°N to 70°S latitude (Cogliati et al. 2021). A cloud-free PRISMA scene was successfully captured over the study area on December 4th, 2022. The hyperspectral data was obtained from the PRISMA mission catalog website (http://prisma-i.it) to Level 2D (reflectance) products.

To optimize the dataset, 234 bands were excluded due to factors like water vapor, noise, and detector overlap. The excluded bands were those with wavelengths ≤ 456, 719-739, 760-770, 813, 951, 962, 973, 855-960, 1120-1163, 1251-1284, 1317-1534, 1765-2027, and ≥ 2350 nm. The exclusion was determined by visually comparing the soil ground reflectance spectra obtained nearly simultaneously using the ASD FieldSpec Pro spectroradiometer. This refinement yielded a dataset comprising 134 reflectance bands, which were utilized for all PRISMA images in this study.

Despite the geocoded nature of the L2D PRISMA images (using Datum: WGS-84 and Projection: UTM 24 S), a minor, non-uniform shift (maximum 5 pixels) persisted across images when compared to ancillary digital cartography and vectorized shape files of the fields of interest. To address this, all images were resampled using the AROSICS function in QGIS (Scheffler et al. 2017). This resampling aimed to co-register the images, aligning them to the field corners' vector grid. This step was crucial both to establish a consistent data stack layer for subsequent multitemporal analysis and to facilitate accurate extraction of PRISMA spectra corresponding to ground-collected field soil samples.

4.3.1.3 Sentinel-2

Sentinel-2 Multi-Spectral Instrument (S2/MSI) data was obtained within the Google Earth Engine (GEE) environment for the study area at the same date of the PRISMA and EnMAP acquisitions. The image was selected from the S2/MSI level 2A (COPERNICUS/S2_SR in GEE). Sentinel-2 pixels affected by clouds and clouds' shadows were masked using the 'QA60' bitmask band for cirrus and opaque clouds and the 'MSK_CLDPRB' for clouds. Only the bands B2 (central wavelength 490 nm), B3 (560 nm), B4 (665 nm), B5 (705 nm), B6 (740 nm), B7 (783 nm), B8 (842 nm), B8a (865 nm), B11 (1610 nm) and B12 (2190 nm) were selected.

4.3.2 Bare soils extraction

Prior to soil sampling in the field, areas with pixels that corresponded to bare soil conditions were analyzed using PRISMA and ENMAP images. The soil masks were created following the methods from HYSOMAP/ENSOMAP algorithms (Chabrillat et al. 2016, Mielke et al. 2018), using a set of spectral indices and thresholds in order to ensure using only bare soil spectra for model calibration, validation and mapping. Bare soil pixels were selected with the Normalized Difference Red Blue Index (NDRBI) < 1 to cover water bodies, the normalized difference vegetation index (NDVI) < 0.3 for green vegetation and the normalized cellulose absorption index (NCAI) < 0.03 to cover dry vegetation, as described from Eq. 1 to 3.

$$NDRBI = \frac{\rho_{660} - \rho_{460}}{\rho_{660} + \rho_{460}} \tag{1}$$

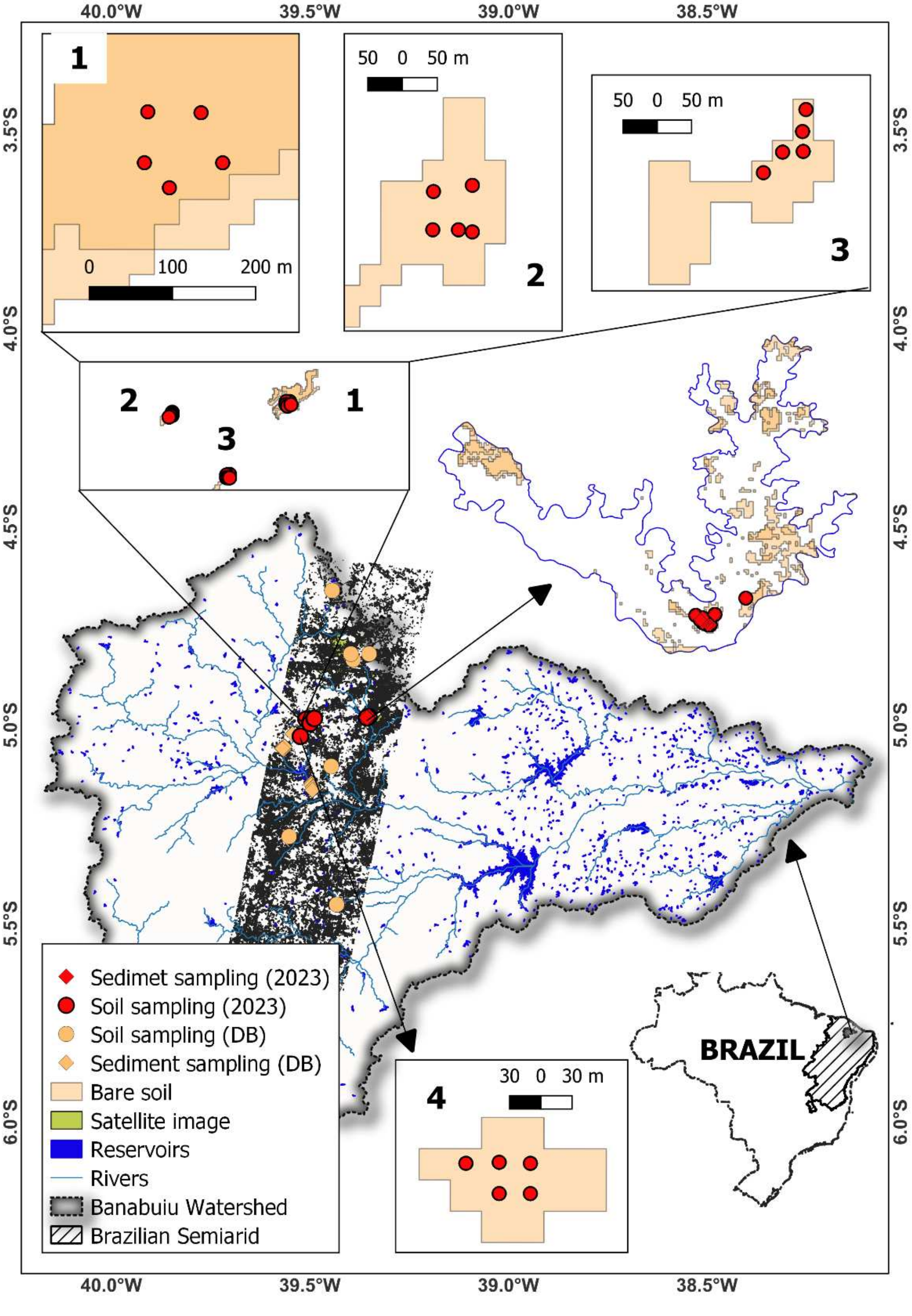
$$NDVI = \frac{\rho_{800} - \rho_{660}}{\rho_{800} + \rho_{660}} \tag{2}$$

$$NCAI = \frac{0.5 \times (\rho_{2000} + \rho_{2200}) - \rho_{2100}}{0.5 \times (\rho_{2000} + \rho_{2200}) + \rho_{2100}} \tag{3}$$

4.3.3 Field sampling and laboratory analysis

After identifying bare soil areas in the Banabuiú River Basin, a field campaign was performed on January 25th, 2023 and a total of 31 samples were collected. The samples were collected in 5 different areas: 11 samples of sediment were collected in the reservoir Pirabibu and 20 samples of soil were collected in 4 agricultural areas in the region (Fig. 2). Each sample consisted of five sub-samples taken within a radius of 5 m around a central location and collected for the depth layer 0-10 cm. The soil and sediment samples were analyzed to determine: the electrical conductivity (EC), clay and organic carbon content (SOC). The EC was analyzed after a preparation of a saturation paste by addition of water to the sample until saturation, and direct reading with a conductivity; the granulometry was performed using the pipette method, with agitation and suspension of the silt and clay fractions in dispersing solution, and quantification of the suspended fraction after sedimentation; and the SOC, by an oxidation of organic matter via a wet process with potassium dichromate in a sulfuric medium. The excess dichromate after oxidation is titrated with a standard solution of ferrous ammonium sulphate (EMBRAPA 2017).

Figure 2 - Location of the study area and the distribution of soil and sediment sample collection points.



4.3.4 Soil and sediment database

Besides the samples collected on January 2023, this study is also based on a database of physicochemical properties for (i) sediments performed by us (Brosinsky et al., 2017; Braga et al., 2017; Carvalho et al., 2022) containing 168 samples to 6 different reservoirs, and for (ii) soil provided by the Meteorology and Water Resources Foundation of Ceará (FUNCEME) containing more than 200 samples across the study area. However, after masking cloud, dry and green vegetation areas, as well as flooded areas, to each satellite, only a few samples were selected and they are described in Table 1. Further details about the sampling process can be consult in our latest study (Braga et al 2023).

Table 1 - Number of bare soil samples for each satellite evaluated

Satellite	Numbers of bare soils samples	
	Soil	Sediment
EnMAP	**33**	**26**
PRISMA	**31**	**19**
Sentinel-2	**53**	**24**

On the other hand, the laboratory spectral database contains data only for 125 sediment samples, performed by Brosinsky et al. (2017) and Carvalho et al. (2022), and the soil spectral database is composed only of the 20 samples collected by this study and described in section 4.3.3.

4.3.5 Spectral measurements

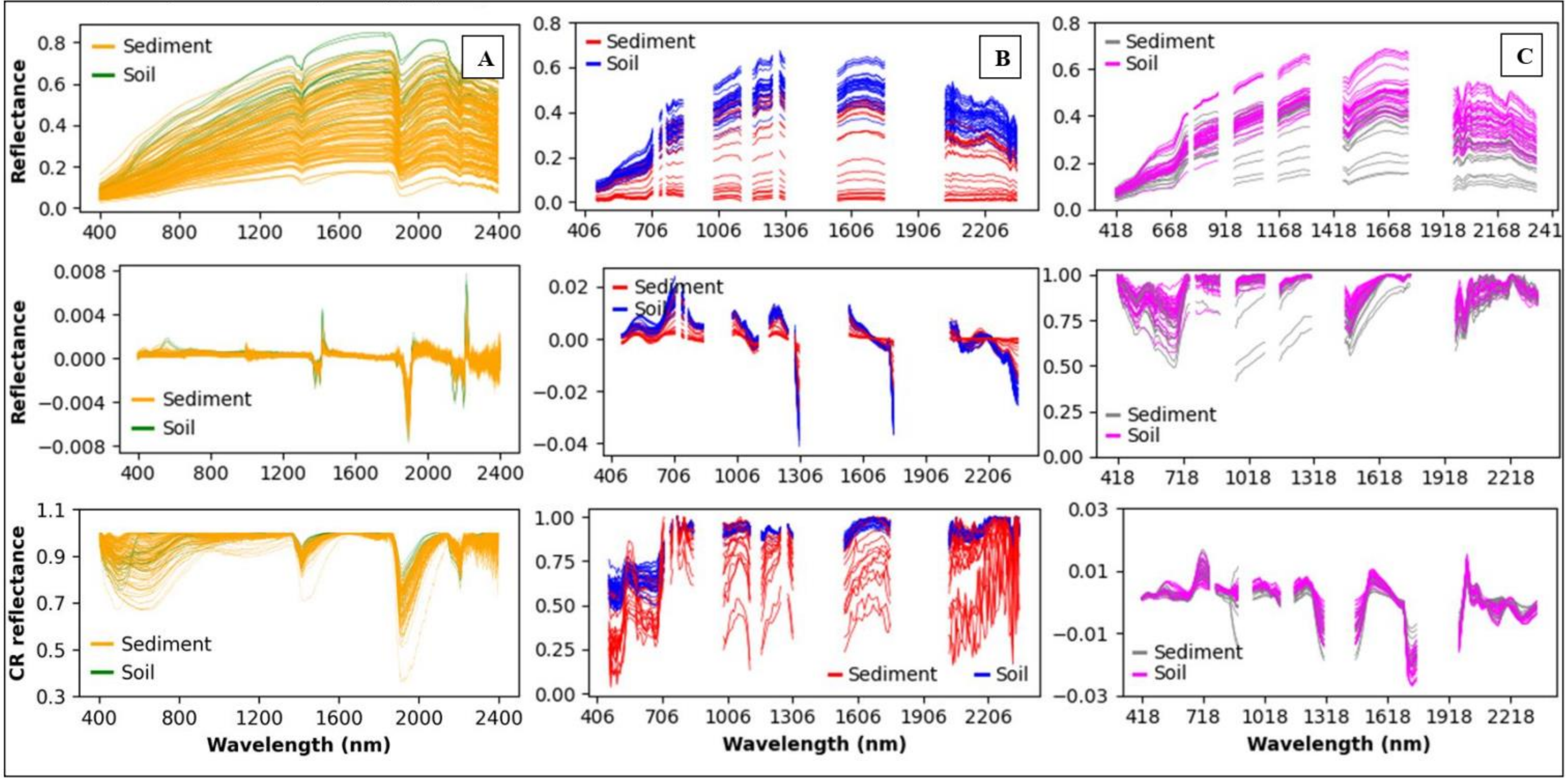
After collection in the field, each soil and sediment sample were taken to an oven at 45°C for 24 hours to dry completely, placed in a black plastic container measuring 5 cm in diameter and 15 mm in height and taken to the Geoprocessing Laboratory of the Agricultural Engineering Department at the Federal University of Ceará - Brazil, for spectral measurements. Spectral readings were taken in a darkroom in a climate-controlled environment, using a Hi-Brite contact probe coupled to a FieldSpec Pro FR3 spectrometer, which collects data for wavelengths from 350 to 2500 nm. The equipment combines three spectrometers with spectral resolutions of 3 nm and 10 nm resampled to 1 nm, and performs real-time reflectance calculations with a full-angle cone of 25 acceptance fields of view (ASD, 1999). The sensor was calibrated every 20 minutes using a Lambertian plate (white reference), in which 100% of the input energy is reflected in all directions (Oliveira et al. 2020) The spectral responses were collected at three random points on the same sample and each point represented the arithmetic mean of 50 spectral readings, allowing each sample to be characterized by the total mean value of 150 spectra/sample. Finally, the digital number (DN) values of the soil samples were converted into reflectance using ViewSpecPro 6.2 software.

4.3.6 Pre-processing of the spectra

For laboratory spectra and hyperspectral data, two types of pre-processing were performed: (1) smoothed first-derivative spectra using the Savitzky–Golay technique (FD-SG) and (3) reflectance spectra with the continuum removed (CR). The Savitzky–Golay technique for first-derivative (FD-SG) processing is a method designed to eliminate baseline interference from spectra while enhancing absorption characteristics. The computation of FD-SG was executed through the utilization of the Savitzky–Golay smoothing method, as outlined in the work of Savitzky and Golay in 1964. A 2nd order polynomial and a window size of 13 and calculated the first derivative using the python function savgol_filter (package:signal). Vasques et al. (2008) demonstrated in their research that the Savitzky–Golay derivative approach consistently produced the most effective preprocessing transformations.

In the determination of the continuum removed spectra (CR), following the method of Kokaly and Clark in 1999, a convex hull (representing the continuum line) was fitted to the spectral curve. This curve was then divided at each wavelength by the convex hull. Wavelength regions lying on the convex hull, such as the initial and final bands, were assigned a value of 1. Conversely, regions residing within absorption bands received values ranging between 0 and 1. Consequently, the CR procedure minimizes disparities in brightness and accentuates the absorption bands within the spectra. The ConvexHull Python package was employed to execute the continuum removal process.

Figure 3 - Raw reflectance spectra (R) (a), first-derivative spectra smoothened with SG (FD-SG) (b) and continuum removed spectra (CR) (c) of laboratory (left), PRISMA (center) and ENMAP spectra (right).



4.3.7 Data Analysis

4.3.7.1 Spectra indexes

4.3.7.1.1 Salinity analysis

To explore the relationship between soil Electrical Conductivity (ECe) and the corresponding reflectance spectra, linear regressions of three indices were evaluated: the difference index (DI), the normalized difference index (NDI), and ratio index (RI) as outlined from Eq. 4 to Eq. 6. All possible combinations of narrow spectral bands within the range of 400 to 2,400 nm (non-excluded after spectra pre-processing) were considered and 2-D correlograms based on the coefficients of determination (R²) were constructed to evaluated the indices performance.

$$DI = R_i - R_j \tag{4}$$

$$NDI = \frac{R_i - R_j}{R_i + R_j} \tag{5}$$

$$RI = \frac{R_i}{R_j} \tag{6}$$

4.3.7.1.2 Soil organic carbon

Before applying the indices, the SOC values of all the samples were converted into a normal distribution by calculating the double square root of the SOC content (Osborne and Waters, 2002; Bartholomeus et al 2008). Based on the VIS wavelength region, three indices were calculated. The first two indices were demonstrated by Bartholomeus et al. (2008), with the first based on the general decrease in reflectance between 400 and 700 nm (Eq. 7) and the second index based on the slope in the VIS between the 400 and 700 nm wavelengths, which varies with SOC content (Eq. 8). The third index evaluated was determined by Thaler et al. (2019) and is shown in Eq. 9.

$$SOC1 = \frac{1}{\Sigma_{i=464}^{699} Ri} \tag{7}$$

$$SOC2 = \frac{1}{slope(R_{464:699})} \tag{8}$$

$$SOC3 = \frac{R_{478}}{R_{546} \times R_{660}} \quad (9)$$

4.3.7.1.3 Clay fraction

To predict the clay content in the soil, the SWIR FI index (Eq. 10) presented by Levin et al. (2007) and an index based on the absorption depth of the removal of the continuum between the wavelengths 2120-2250 nm (Chabrillat et al. 2011) (Eq. 11) were evaluated.

$$SWIRFI = \frac{(R_{2133})^2}{R_{2225} \times {R_{2209}}^3} \quad (10)$$

$$Clay\ CRAD = AD(R_{2120:2250}) \quad (11)$$

4.3.7.2 PLSR model

The PLSR method is a widely used regression technique in chemometrics, and it was first introduced and statistically described by Geladi and Kowalski (1986) and Wold et al. (2001). PLSR is frequently employed for conducting quantitative spectral analyses (Bilgili et al., 2011; Farifteh et al., 2007). The algorithm utilizes a linear multivariate model to establish a relationship between predictor (X) and response (Y) variables. It selects successive orthogonal (latent) factors to maximize the covariance between X and Y or the covariance between the spectra (X) and a measured soil property (Y).

In our study, we used the Python package SKLEARN to estimate the contents of EC, SOC, and clay from spectral data via PLSR modeling. Prior to PLSR modeling, due to significant skewness, the soil properties were transformed to achieve a normal distribution using the natural logarithm. Regression models were developed individually for each type of sample (soil and sediment), as well as for all samples combined. PLSR was performed using leave-one-out cross-validation (LOOCV), with a maximum of 20 factors allowed.

4.3.8 Statistical metrics

To evaluate the performance of each index, the following statistical metrics were calculated: coefficient of determination (R^2), root mean square error (RMSE) and the prediction deviation ratio (RPD) (Eq. 12 to 14).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{N}(Y_i - \bar{Y}_i)^2} \tag{12}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(\hat{Y}_i - Y_i)^2}{N}} \tag{13}$$

$$RPD = \frac{\sigma_{Yo}}{RMSE} \tag{14}$$

where Ŷ represents the values estimated by the index or models in the i-th observation; Yi are the values observed in the laboratory in the i-th observation; $\bar{Y}_i$ represents the mean of the observed values; N is the number of observations; and σ is the standard deviation for the measured values.

Same statistic metrics were calculated to identify the optimal cross-validated calibration model. Typically, the model with the highest cross-validated R^2 value and the lowest RMSE value, while aiming for an RPD > 1.4, is selected.

4.4 Results

4.4.1 Descriptive Statistics of Measured Soil Attributes

The descriptive statistics for all samples of soil and sediment, respectively, are shown in Table 2. The results show that the soil in the study area can be considered slightly saline, according to Richards (1954), although it has a large range of variation from 0.1 to 6.12 dS/m. Despite the high coefficient of variation (CV) of the sediment samples, the sediment's mean salinity was almost 300% higher when compared to the soil. This behavior has already been observed in our previous studies (Braga et al. 2019, Braga et al. 2023, Carvalho et al. 2022) and reinforces the importance of studying salinity in the sediment component. When evaluating the mean Ca^{2+}, Mg^{2+}, Na^+ and K^+ values of the samples, it can be seen that, in general, all the groups had high levels of exchangeable and soluble cations. The predominant cation in both soil and sediment is Ca^{2+} (55 and 59% of the total cations for soil and sediment, respectively). However, the increased concentration of Na^+ in the sediment (3 times higher) can be a cause for concern, since high concentrations of this element can increase the Sodium Adsorption Ratio (SAR) of the soil. Elevated values of this parameter lead to soil waterproofing and stiffness, causing a reduction in its hydraulic conductivity and increased resistance to the penetration of plant roots (da Costa, 2004).

The sediment also showed higher concentrations of organic carbon compared to the soil. For the sediment samples, the SOC content varied between 0.3 and 34.4 g kg^{-1} with a mean value of 14.4 g kg^{-1}. This result may be associated with the higher concentrations of nitrogen and organic matter in this group. Higher SOC concentrations have a positive correlation with the content of fine soil particles, which contribute to the protection of organic matter due to the formation of organo-mineral complexes that are resistant to microbial degradation (Pietrzykowski and Chodak, 2014). In fact, the textural composition in the sediment indicated that the silt and clay fraction was predominant, while the soil had higher levels of sand.

Table 2 – Descriptive statistics of soil and sediment attributes for the database analyzed.

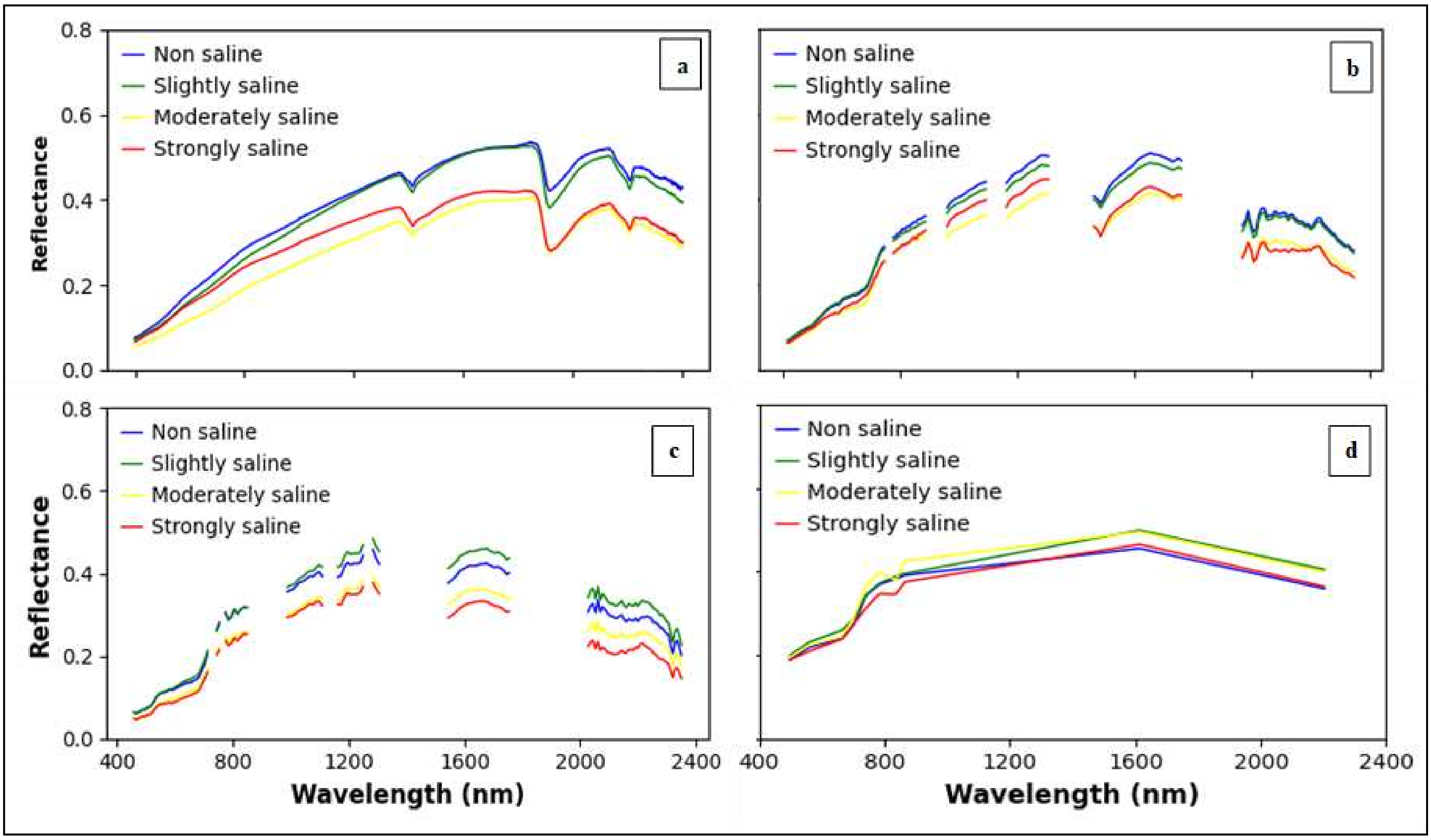
Sample	SP	EC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SOC	N	O.M	$P_{available}$	Clay	Silt	Sand
		dS m^{-1}	cmol kg^{-1}				g kg^{-1}				%		
Soil	Mean	0.74	5.43	3.68	0.47	0.2	3.23	0.37	4.99	0.01	22.9	15.4	61.4
	SD	0.93	4.29	2.93	0.76	0.1	2.64	0.2	4.28	0.02	11.3	8.13	17.7
	Max	6.12	18.38	13.97	4.17	0.68	12.02	1.02	20.69	0.18	49.60	38.20	95.10
	Min	0.08	0.10	0.10	0.01	0.01	0.01	0.01	0.02	0.001	2.00	0.10	18.70
	CV (%)	127	79	80	161	89	82	54	86	226	50	53	29
Sediment	Mean	2.1	12.5	6.3	1.4	1.1	14.4	1.6	32.9	0.03	32.0	31.4	36.4
	SD	2.1	8.3	4.1	1.9	0.8	8.4	0.9	23.9	0.03	18.8	13.2	27.3
	Max	8.6	34.8	17.7	10.1	3.2	34.4	4.6	94.8	0.15	74.4	57.9	98.6
	Min	0.1	0.5	0.6	0.0	0.0	0.3	0.1	0.9	0.001	0.6	0.8	1.0
	CV (%)	97	67	66	144	73	59	57	73	99	59	42	75

4.4.2 Spectral characteristics of salt-affected soils

Figure 3 shows the spectra of the soil and sediment samples described in topic 3.4 according to the salinity levels suggested by Richards (1954). For each class, an average spectrum was calculated, however, since the dataset contains only the sample points after applying the water, vegetation and cloud masks, the class of extremely saline soils and/or sediments (EC > 2.4 dS/m) was not represented. It can be seen that the spectra of all samples have similar shapes, with considerable overlap in some wavelengths. It can also be seen that, with the exception of the spectral responses from the Sentinel-2 satellite, the spectra representing the different salinity ranges (Fig. 3a-c) showed an inverse relationship with reflectance, in summary: higher the salinity level, lower is the samples reflectance. This result suggests that salinization may be associated with an increase in the soil's moisture content. Since the predominant salts in this region consist mainly of highly hygroscopic salts, such as $MgCl_2$, capable of absorbing water vapor, it is possible to observe an increase in soil moisture. This behavior has also been observed in other studies (Qian et al. 2019, Sidike et al. 2014, Pessoa et al 2016, Nawar et al 2015).

The spectral curve of the samples measured in the laboratory (Fig. 4a) for each salinity level exhibited strong absorption properties at wavelengths around 1,400, 1,900 and 2,200 nm. The first two absorption regions of the spectrum (bands removed in the satellite images) are linked to specific salts (such as $CaCl_2$ and $MgCl_2$) present in the soils, relating to the internal vibrational processes of anions (such as OH^- and the Al-OH group) or to water molecules retained or adsorbed in the crystalline structure of the soil (Hunt, 1977; Crowley, 1991). On the other hand, the absorption band centered at 2200 nm is generally associated with the hydroxyl groups present in clay minerals. Among the 400 to 1000 nm range, it was not possible to distinguish any marked absorption peaks between the laboratory spectra and those of the hyperspectral satellites for the different salinity levels. The reflectance curves produced by the EnMAP satellite (Fig 4b) show two absorption peaks around 1,460 and 1,960 nm and a reflectance peak near 2200 nm. The PRISMA satellite spectral curve shows slight absorption in the 900, 2100 and 2300 nm bands.

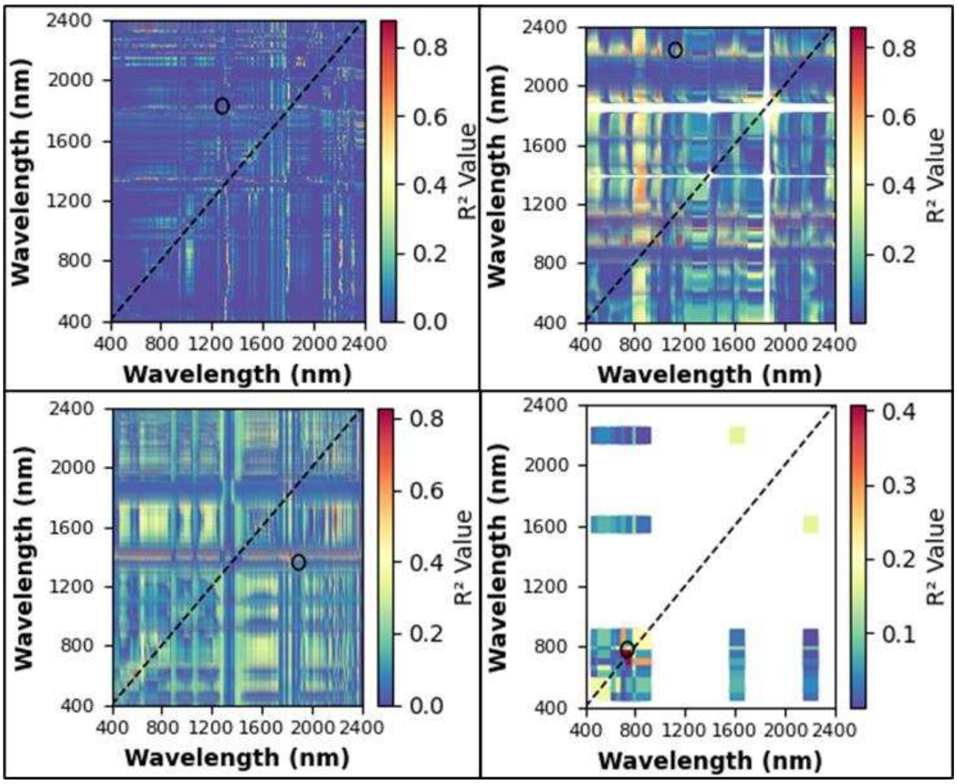
Figure 4 - Reflectance of five salinity classes, according Richards (1994), for laboratory spectra (a), spectra from ENMAP (b), PRISMA (c), and Sentinel-2 images (d).



4.4.3 Relationship between soil salinity and the spectral indices

Through the analysis of the 2-D correlograms, it was possible to evaluate better pair combinations for all wavelengths between 400 and 2500 nm for: the three different indices (DI, RI and NDI); the three dataset combinations (soil, sediment, soil-sediment combination); the three types of spectrum pre-processing (raw, FD-SG and CR); as well as the 4 different sources for obtaining the spectrum curve (ASD laboratory, EnMAP, PRISMA and SENTINEL-2 satellites), resulting in 90 correlograms. Nevertheless, only the best 2-D correlogram between EC and spectral indices for each data source is shown in Fig. 5. A table with information on all the correlograms is available as supplementary material (Table S1).

Figure 5 - The 2-D correlogram of best R² between EC and spectral indices for (a) lab, (b) EnMAP, (c) PRISMA and (d) SENTINEL-2 spectra.



In general, the use of salinity indices seems to be a promising approach to assessing soil salinity by remote sensing. A consistent correlation was observed between the difference index (DI), ratio index (RI) and normalized difference index (NDI) and soil salinity, especially in the visible and near-infrared spectrum bands. However, the efficiency of these indices as predictors of soil salinity showed significant variations in relation to wavelength. When comparing the three indices, especially in data from hyperspectral satellites and laboratory spectroradiometers, the ratio index (RI) distinguished itself by presenting more robust correlations with salinity, often showing determination coefficients (R²) above 0.6. On the other hand, the difference index (DI) showed inferior performance in all combinations of data set and pre-processing, but proved to be more effective when dealing with data from the SENTINEL-2 multispectral satellite, with a R² of 0.41 to the sediment dataset. These findings indicate the sensitivity of spectral indices to wavelength variation, suggesting the need for careful selection when choosing the combination of indices and data sources for soil salinity estimation.

Testing the various combinations of datasets reveals that the exclusive use of the sediment-only set results in a slightly higher R². However, it is important to consider the possible influence of the limited number of sediment samples on models based on satellite spectral data (Table 1). Additionally, when evaluating the performance of the indices on laboratory data, the dataset made up of only soil information showed better performance, with higher R².

Additional analysis conducted on the spectra processed using the Savitzky-Golay filter (FD-SG) and continuum removal (CR) in all possible band combinations showed a significant correlation between electrical conductivity and the indices constructed. Although the results derived from the CR spectra generally improved the performance of the indices compared to the raw spectra, they did not achieve the same effectiveness as those based on FD-SG. When analyzing the combinations of wavelengths obtained in the laboratory for the D, RI and NDI indices, those corresponding to 922 and 941 nm, 1364 and 1815 nm, and 1285 and 1827 nm, respectively, stood out (Table S1). Particularly noteworthy is that the last combination mentioned had the highest R² of 0.88 for the spectra of the first derivative with SG filter, showing a solid performance of the index (Fig. 4).

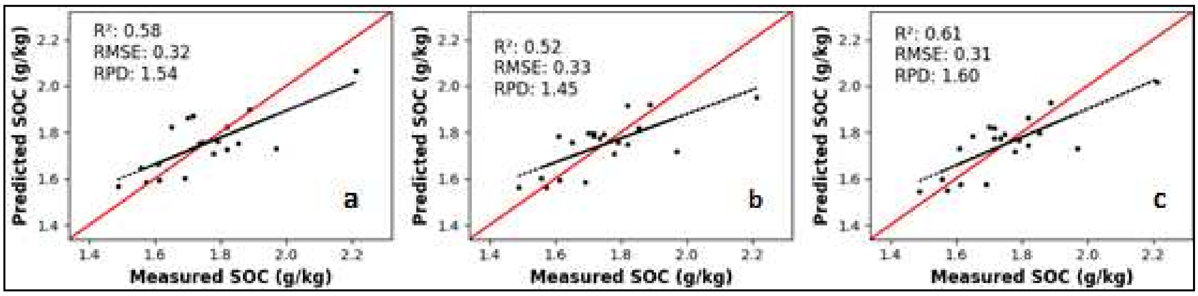
Finally, when evaluating the performance of the indices for the different satellites, the EnMAP satellite performed slightly better. The most effective combination for EnMAP was obtained for the spectrum pre-processed with FD-SG, which showed an R² of 0.91, while for PRISMA the best combination (R² = 0.83) was observed for CR spectrum, both for the RI index and using only the sediment dataset (Fig. 4).

4.4.4 Relationship between SOC and the spectral features

Through this study, it was found that applying SOC indices proved to be effective only for spectral data acquired on a laboratory scale, since the models that used reflectance data obtained from the PRISMA and EnMAP hyperspectral satellites did not achieve the same effectiveness, showing RPD values of less than 1.4 for all three of the different indices evaluated. Furthermore, this performance was observed for all combinations of dataset and spectrum pre-processing, which suggests that the application of these indices may not be viable in large areas or for studies that rely exclusively on satellite data. The statistical metrics analysis revealed that pre-processing the spectrum with the first derivative spectra smoothed using the Savitzky-Golay technique (FD-SG) and Continuum Removal (CR) did not improve the indices explanatory capacity, with CR being the technique that degraded the models' performance the most.

In addition, it was observed that, similar to the salinity indices, splitting the database into sediment or soil-only improved the indices' predictive capacity for the models built at the space and laboratory scales, respectively. For the latter, R² values of 0.58, 0.52 and 0.61 were observed for the SOC1, SOC2 and SOC3 indices, respectively (Fig. 6). When comparing the three indices evaluated, the SOC3 index showed a slight improvement in the SOC estimate. This result was expected, as this index was built from a large database of a corn agricultural area in the central part of the United States (Thaler et al. 2019), a land use condition similar to the area from which the soils in this study were sampled. Other authors have also observed a satisfactory performance of VIS-SWIR-based indices in estimating soil organic carbon (Ribeiro et al. 2023; Ribeiro et al. 2021). Péon et al (2017) has shown the spectral index (SI) with the form of the normalized difference vegetation index for the wavelengths 1001 and 679 nm is useful as an SOC index, with a maximum R^2 value of 0.56 for a satellite hyperspectral measurement from 39 soil samples collected in northwestern Spain.

Figure 6 - Performance for raw reflectance of laboratory spectra to SOC1(a), SOC2 (b) and SOC3 (c) for soil-only database.



4.4.5 Relationship between clay content and the spectral features

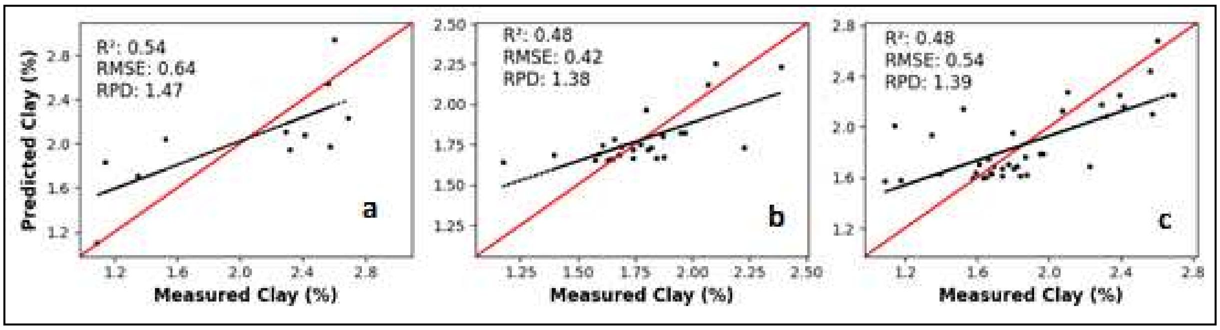
Various spectral indices have been used to estimate soil clay content (Drury, 1987; Levin et al. 2007; Chabrillat et al. 2011; Gomez et al. 2016; Danoedoro et al. 2015). These methods are based on the physical analysis of spectral reflectance, such as the slope or depth value of the absorption band, as in the index proposed by Chabrillat et al. (2011). In addition, there are also approaches that include combining the spectral reflectance of two or more wavelengths to estimate the relative abundance of features of interest, such as the fine particle index developed by Levin et al. (2007), applied to wavelengths in the short-wave infrared (SWIR). These two indices, which were evaluated in this study, enable the quantification of minerals or soil physicochemical properties, providing a valuable approach for predicting soil clay content by remote sensing.

Comparing the performance of those two indices, it was noted that the CRAD index performed slightly better than the SWIR-FI index for most of the cases evaluated, reaching an

R² of around 50% (Figure 7). In addition, as observed for SOC, pre-processing the spectrum by CV or FD-SG did not improve the indices' performance either, and for the clay content parameter, the application of FD-SG sharply reduced the R² values.

When comparing the indices' statistics metrics between the two different hyperspectral satellites and laboratory reflectances, better results were observed for data acquired with the EnMAP space sensor, in which the best model was obtained when using a database containing only sediment points (R² = 0.54, RMSE = 0.64, RPD = 1.47). In fact, dividing the data set into only soil or sediment increased the model's performance (Fig. 6a and Fig. 7b), but when working with the entire data set, which would represent a more robust and reliable model, the index still performed satisfactorily, with a slight decrease in R² and RPD ≥ 1.4 (Fig. 7c).

Figure 7 - Performance of CRAD index for raw reflectance of EnMAP spectra to sediment-only(a), soil-only (b) and all (c) database.



Evaluating the performance of the SWIRFI index, based on the spectral bands at 2130, 2205 and 2224 nm from hyperspectral data acquired at laboratory level, Gomez et al. (2016) observed R² close to 30% for predicting clay content, similar to that observed in this study (Supplementary material). Datt et al. (2003) also observed good results for the Clay Index (CI), using the Hyperion bands at 2193, 2203 and 2214 nm. Shabou et al. (2015) used linear regression models to establish the relationship between the MID-infrared index, derived from Landsat-TM images, and the clay content in the Kairouan plain, located in central Tunisia.

4.4.6 Performance of PLSR

Table 4 shows the results of the cross-validation models obtained by applying PLSR to different pre-processing methods, acquisition scale and dataset arrangement of the soil reflectance. After identifying the ideal number of latent factors for the cross-validation models and analyzing the statistical metrics derived from them, it was possible to estimate soil EC. However, it should be noted that none of the models generated for the space scale of data acquisition performed satisfactorily, as evidenced by RPD values less than 1.2, indicating the unreliability of the predictive models. It was also observed that, even after applying spectrum pre-processing techniques (FD-SG and CR) or the dataset splitting, there was no significant improvement in PLSR performance. On the other hand, for soil reflectance obtained in the laboratory, PLSR performed well, especially for the untransformed spectra. In this scenario, when comparing the measured values for EC as a function of the values estimated by the PLSR model, an $R^2 = 0.49$, RMSE = 0.73 (2.1 dS m^{-1}) and RPD = 1.41 were observed (as shown in Figure 6A).

Table 3 – Cross-validation results for the PLSR models for estimating EC using the 400–2400 nm spectrum.

Spectra source	**Spectral Pré-processing**	**Dataset Arrangement**	**R²**	**RMSE**	**RPD**
Laboratory	Untransformed	All dataset	0.49	0.73	1.41
		Soil only	0.14	0.39	0.96
		Sediment only	0.38	0.81	1.27
	FD-SG	All dataset	0.15	0.95	1.09
		Soil only	0.01	0.45	0.83
		Sediment only	0.02	1.02	1.01
	CR	All dataset	0.10	0.97	1.06
		Soil only	0.01	0.45	0.83
		Sediment only	0.03	1.01	1.02
EnMAP satellite	Untransformed	All dataset	0.24	0.60	1.16
		Soil only	0.02	0.46	0.89
		Sediment only	0.14	0.8	1.13
	FD-SG	All dataset	0.19	0.62	1.12
		Soil only	0.04	0.51	0.8
		Sediment only	0.14	0.8	1.13
	CR	All dataset	0.22	0.6	1.15
		Soil only	0.14	0.58	0.70
		Sediment only	0.12	0.91	0.99
PRISMA satellite	Untransformed	All dataset	0.06	0.48	1.04
		Soil only	0.05	0.39	0.99
		Sediment only	0.04	0.62	1.02
	FD-SG	All dataset	0.15	0.46	1.10
		Soil only	0.03	0.37	1.03
		Sediment only	0.59	0.77	0.83
	CR	All dataset	0.06	0.48	1.04

		Soil only	0.02	0.38	1.01
		Sediment only	0.17	0.66	0.97
Sentinel 2 satellite	Untransformed	All dataset	0.02	0.58	1
		Soil only	0.01	0.47	1
		Sediment only	0.02	0.68	1.03

NF: number of factors; R²: coefficient of determination; RMSE: Root Mean Square Error and RPD: Ratio of Prediction Deviation

A strong relationship between EC and soil reflectance in the NIR region can be easily verified by the multiple peaks in the PLSR coefficients (Figures 6A-right). Our result is in accordance with previous findings (Farifteh et al., 2007; Weng et al., 2008; Bilgili et al., 2011; Mashimbye et al., 2012). The use of a linear regression model with an unprocessed spectral band for spectral regions 2100-2300 nm revealed a strong correlation with EC, indicating adequate sensitivity of the hyperspectral satellites evaluated in assessing soil salt content in semi-arid environments.

As with EC, PLSR was carried out for soil carbon content (SOC) using all the spectral bands with unprocessed reflectance data and their transformations, and the results can be seen in Table 4. In this study, there was a tendency for the models to fit the subsets of samples (sediment only or soil only) more effectively than the entire dataset. The application of spectrum smoothing techniques aims to mitigate the random noise inherent in the original data, resulting in an improvement in the signal-to-noise ratio in the spectra, however this spectral pre-processing only improved the performance of the model built from reflectance acquired with PRISMA hyperspectral satellite images, unlike that observed by Mousavi et al. (2020) and Ribeiro et al. (2021). Better performance was found for models built after determining the smoothed First Derivative with the Savitz-Golay technique, where a coefficient of determination of 34% was observed. Despite this, the model did not achieve sufficient RPD values to be considered valid.

Table 4 – Cross-validation results for the PLSR models for estimating SOC using the 400–2400 nm spectrum.

Spectra source	Spectral Pre-processing	Dataset Arrangement	R^2	RMSE	RPD
Laboratory	Untransformed	All dataset	0.45	0.46	1.36
		Soil only	0.32	0.29	1.24
		Sediment only	0.39	0.49	1.28
	FD-SG	All dataset	0.08	0.59	1.04
		Soil only	0.06	0.37	0.88
		Sediment only	0.04	0.62	1.03
	CR	All dataset	0.00	0.61	1.00
		Soil only	0.09	0.37	0.87
		Sediment only	0.02	0.64	0.99
EnMAP satellite	Untransformed	All dataset	0.21	0.57	1.14
		Soil only	0.45	0.39	1.38
		Sediment only	0.24	0.20	1.2
	FD-SG	All dataset	0.16	0.59	1.11
		Soil only	0.18	0.48	1.12
		Sediment only	0.05	0.28	0.87
	CR	All dataset	0.11	0.60	1.07
		Soil only	0.02	0.6	0.89
		Sediment only	0.08	0.26	0.93
PRISMA satellite	Untransformed	All dataset	0.08	0.59	1.05
		Soil only	0.08	0.59	1.05
		Sediment only	0.10	0.34	1.10
	FD-SG	All dataset	0.08	0.59	1.05
		Soil only	0.22	0.44	1.15
		Sediment only	0.34	0.29	1.29
	CR	All dataset	0.19	0.55	1.12
		Soil only	0.13	0.53	0.96
		Sediment only	0.05	0.81	0.46
Sentinel 2 satellite	Untransformed	All dataset	0.08	0.71	1.05
		Soil only	0.08	0.58	0.97
		Sediment only	0.60	0.76	1.61

Despite the low RMSE and satisfactory R^2 values, the use of data obtained from hyperspectral satellites or even on a laboratory scale was not enough to generate effective models ($RPD < 1.4$) for predicting SOC. Contrary to what was observed for the previous analyses, only the PLSR built for images of sediment points from the Sentinel-2 multispectral satellite resulted in a model with an RPD above 1.4, as well as a reduction in the number of factors and a significant improvement in R^2 to 0.6 (Figure 6B). Similarly to verified by Ribeiro et al. (2021), it was found that the models fitted better to the subsets of samples (sediment dataset) that showed greater variation in the chemical concentration of organic carbon.

Analysis of the PLSR indices and coefficients allowed us to verify the strong influence of spectral reflectance in the VIS region (Figure 6b - right), as observed by Gmur et al. (2012) and Vohland et al. (2014) in estimating SOC. Significant weight for band 11 (centered on 1610 nm) of the Sentinel - 2 satellite was also observed in the construction of the PLSR. According to Ribeiro et al. (2021), when using the first derivative to select spectral bands, bands between 1600 nm and 1800 nm are related to phenolic (O-H) and aliphatic carboxyl (C-H) groups (Fidêncio et al. 2002) and have a strong influence on SOC.

For the soil clay content, the accuracy of the estimate with real satellite data decreased compared to the spectra sampled in the laboratory (Table 5), a result also seen by Mzid et al. (2022). However, unlike what was observed by the author (Mzid et al. 2022), data from the PRISMA and EnMAP hyperspectral satellites do not show similar behavior to laboratory spectral data when estimating soil clay content. Indeed, only for the laboratory scale were observed linear models with RPD values greater than 1.4. For this database, models with maximum values of $R^2 = 0.76$, RMSE = 0.92 and RPD = 2.07 were obtained for untransformed reflectance (Figure 6C). Among the models generated from pre-processed spectra, there was better model performance after applying the CR technique, as observed for the EC variable.

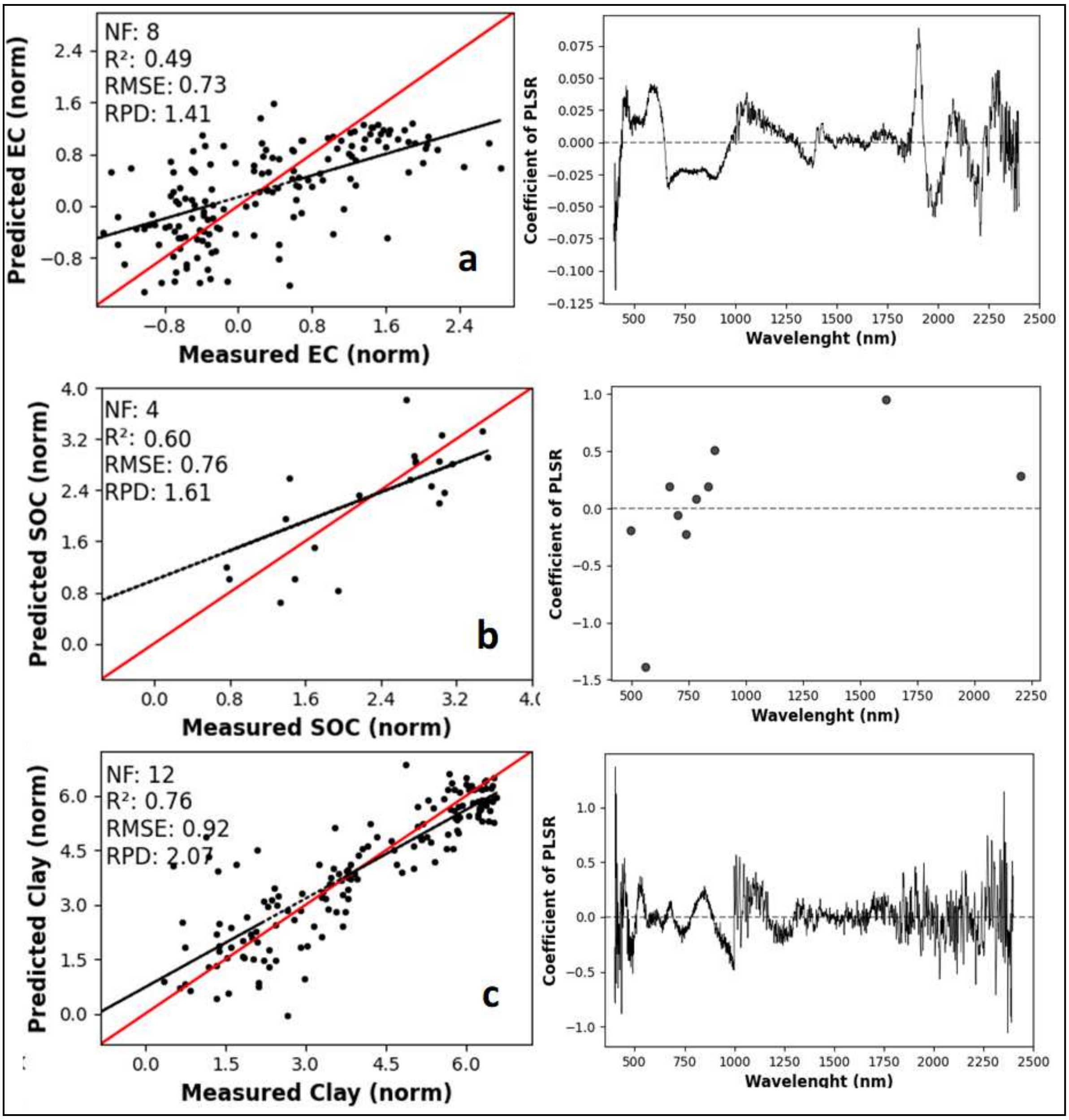
Table 5 – Cross-validation results for the PLSR models for estimating soil clay content using the 400–2500 nm spectrum.

Spectra source	Spectral Pre-processing	Dataset Arrangement	R^2	RMSE	RPD
Laboratory	Untransformed	All dataset	0.76	0.92	2.07
		Soil only	0.01	3.83	0.98
		Sediment only	0.76	0.92	2.03
	FD-SG	All dataset	0.54	1.23	1.48
		Soil only	0.02	0.39	0.93
		Sediment only	0.58	1.23	1.55
	CR	All dataset	0.41	1.40	1.30
		Soil only	0.15	0.38	0.96
		Sediment only	0.60	1.20	1.58
EnMAP satellite	Untransformed	All dataset	0.20	0.80	1.13
		Soil only	0.36	0.45	1.28
		Sediment only	0.13	1.44	0.99
	FD-SG	All dataset	0.14	0.83	1.09
		Soil only	0.31	0.46	1.23
		Sediment only	0.04	1.38	1.03

	CR	All dataset	0.17	0.81	1.11
		Soil only	0.27	0.48	1.19
		Sediment only	0.05	1.32	1.07
PRISMA satellite	Untransformed	All dataset	0.25	0.73	1.17
		Soil only	0.51	0.42	1.45
		Sediment only	0.08	1.35	0.89
	FD-SG	All dataset	0.19	0.76	1.12
		Soil only	0.37	0.47	1.28
		Sediment only	0.04	1.98	0.61
	CR	All dataset	0.15	0.77	1.10
		Soil only	0.38	0.47	1.29
		Sediment only	0.00	7.3	0.16
Sentinel 2 satellite	Untransformed	All dataset	0.27	0.81	1.11
		Soil only	0.27	1.13	1.19
		Sediment only	0.27	0.52	1.18

Furthermore, the statistical metrics confirmed the better estimation accuracy of the hyperspectral imager compared to the multispectral satellites, as expected. Comparing only the performance of the PLSR generated for the two hyperspectral satellites, the model using PRISMA hyperspectral imagery provided the best results for clay estimation, achieving an RPD of 1.45, R^2 of 51 % and RMSE = 0.42, in the case of a model built for soil data only. As observed for SOC, the splitting of the dataset into soil and sediment-only is also capable of increasing the linear model's performance, being the dataset with the greatest CV (in this case soil, as show in Table 2) the one that generates the best results. The composition of the clay minerals in the soil, such as illite, has a strong influence on the bands centered around 2,300 and 2,400 nm (Castaldi et al. 2016). In this study, higher PLSR coefficients were observed for this region of the spectrum. This was also observed by Mzid et al. (2022).

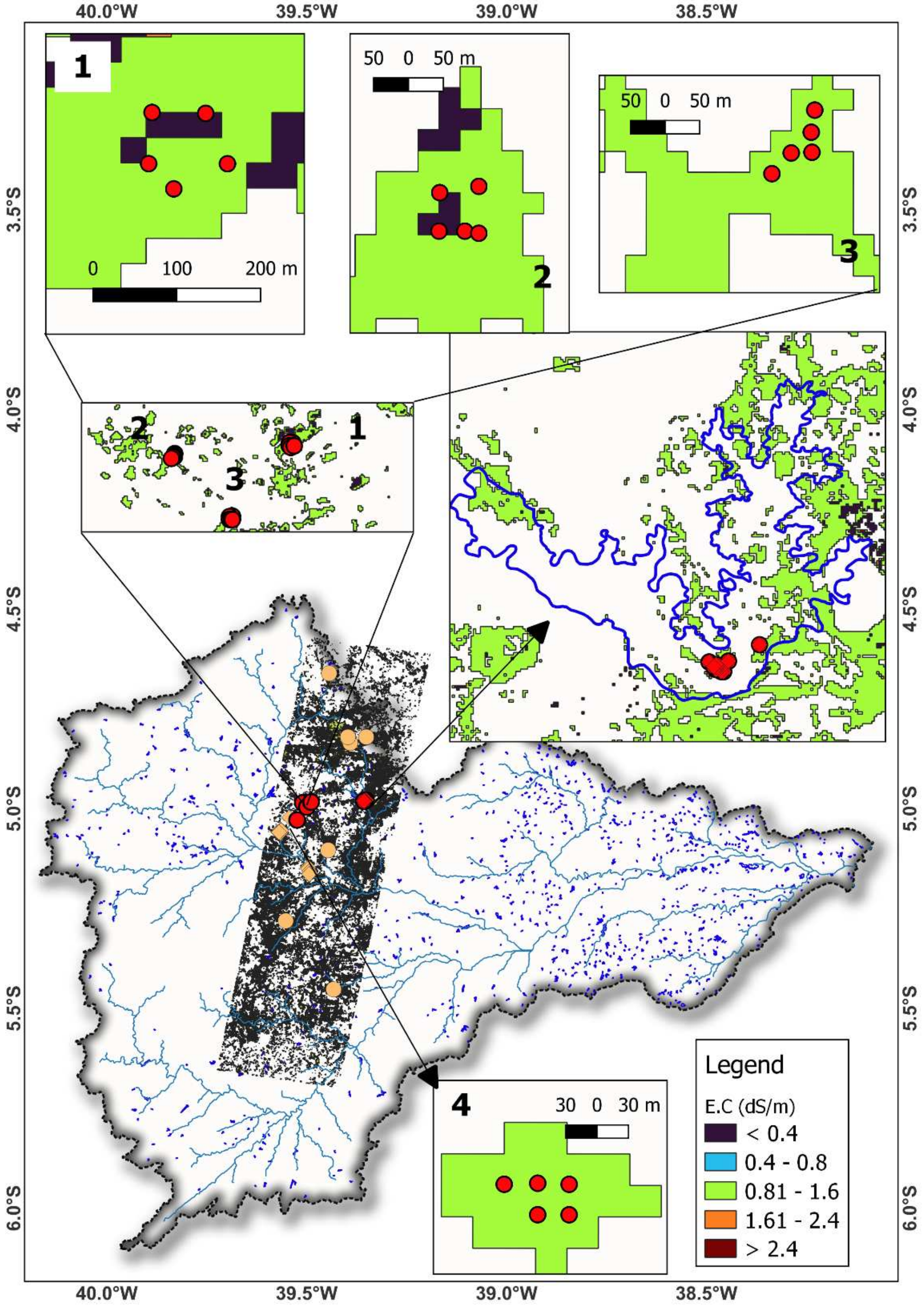
Figure 8 - Best PLSR performance of the models for EC (a), SOC (b) and Clay (c) soil content (left) with regression coefficients for PLSR (right).



4.4.7 Mapping of soil attributes in the study area based on the best models evaluated

Examining the images available for mapping soil salinity in the study area, there is a scarcity of pixels corresponding to exposed sediment (Table 01) due to the presence of different types of cover, such as clouds, vegetation and/or water. Therefore, it seems more careful to employ index models that use the entire data set (soil+sediment), even in the face of the small reduction in model performance, ensuring a more robust approach in the face of the limitations observed. Therefore, the models with the best performance among the three satellite images evaluated were used to create the maps of CE, SOC and clay content (Fig. 09).

Figure 9 - Eletrical conductivity, SOC, and clay content maps for EnMAP, Sentinel-2 and PRISMA best models applied to the satellite imagery, respectively.



4.5 Discussion

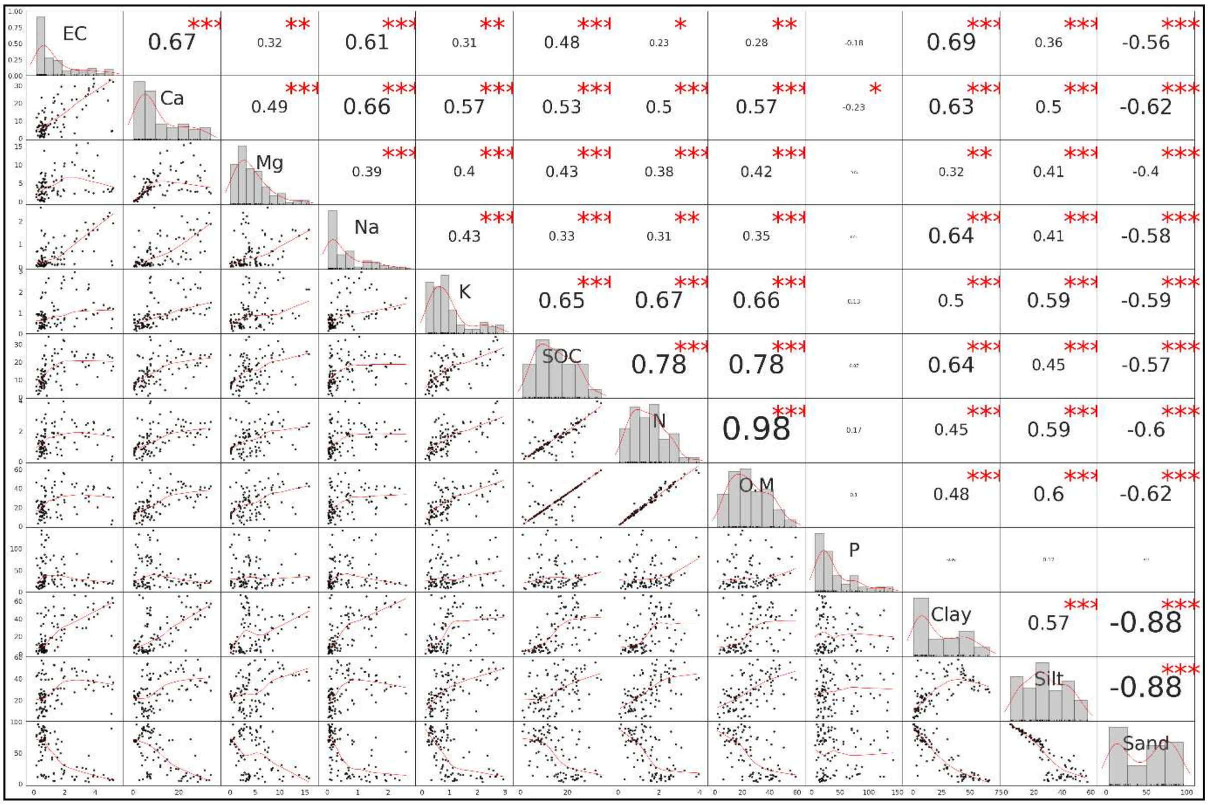
This study represents an initial initiative to evaluate the accuracy of the recently launched hyperspectral satellite EnMAP in assessing and mapping the soil and reservoir sediment properties. To achieve this purpose, real spectra of bare soil acquired by the satellite were used to evaluate methods based in two different approaches: spectral indices and a PLSR linear regression. The predictive capacity of the models in estimating electrical conductivity (EC), organic carbon (SOC) and soil clay content from the spectrum obtained with EnMAP was compared with models using reflectances acquired with the hyperspectral satellite (PRISMA), the multispectral satellite Sentinel-2, as well as spectral curves obtained on a laboratory scale. In addition, two different pre-processing techniques, first derivative smoothed with Savitz-Golay (FD-SG) and the continuum removal (CR), were also applied to the unprocessed spectrum in an attempt to improve the indices and linear models' performance.

In general, pre-processing did not lead to an improvement in the performance of the spectral indices and the PLSR model when trying to reproduce the true concentrations of the chemical elements in the soil and sediment samples, although the prediction of soil electrical conductivity using spectral indices showed a positive influence of pre-processing, especially for FD-SG (Figure 4). While the performance of the salinity indices was markedly improved, the accuracy of the PLSR models was significantly degraded after pre-processing. A similar result was observed by Naibo et al. (2022) for soils and sediments from a watershed located in Southern Brazil. On the other hand, Nawar et al. (2015) observed improvements in the prediction of soil electrical conductivity for both spectral indices and PLSR. Smoothing the spectra removes noise and can eliminate factors that lead to non-linearities (Bilgili et al. 2010), thus reducing the accuracy of the linear PLSR model. The aim of implementing spectrum pre-processing is to enhance weak spectral features, since spectral data is influenced by various soil components, some of which are associated with the specific chemical property under analysis, while others are not (Chabrillat et al., 2019). In addition, it is to reduce physical effects on the spectrum, as highlighted by Demetriades-Shah et al. (1990). An alternative for improving the performance of the linear model could be to apply data-mining techniques, such as the "PARACUDA®" machine (Gholizadeh et al. 2018), since the approach is able to select the best combination from more than 120 pre-processing techniques.

The prediction of soil attributes content by remote sensing is based mainly on variations in the reflectance of the spectrum in the visible and near infrared bands (Kooistra et al. 2003, Bartholomeus et al. 2008). Multivariate statistical techniques such as PLS have been widely used in recent years to estimate the soil properties evaluated, but transferring these models between sensors with different characteristics is a disadvantage of the method (Viscarra Rossel et al., 2006). Thus, the prediction models based on spectral indices related to the soil's biochemical composition have the advantage that the transferability of spectral indices to various sensors appears to be less complicated than that of models based on multivariate techniques (Bartholomeus et al. 2008). This study found that spectral indices performed better than the PLSR model in estimating EC and soil clay content for spectra obtained on a spatial scale. Only when working with reflectances obtained in the laboratory could valid PLSR models (RPD>1.4) be observed in predicting the concentration of these two variables in soil and sediment. This result may be related to a limitation of the PLSR method associated with transforming the matrix of spectral variables into orthogonal factors, because during this process crucial explanatory variables may be lost, reducing the model's performance (Naibo et al. 2022). In addition, Brown et al. (2005) highlight the fact that PLS-based models may be being built indirectly, using lower intensity spectral characteristics of other soil constituents, such as iron oxides.

Figure 10 shows the coefficient of correlation (r) between the soil physic-chemical attributes. By identifying the variables that show the most significant correlations with each other, it is possible to distinguish potential auxiliary predictors in addition to the soil reflectance that have the potential to substantially improve the performance of the PLSR model, as observed by several studies (Bilgili et al. 2011; Brown et al., 2006).

Figure 10 - Correlation matrix of relationships between the soil physic-chemical variables. The numbers represent the correlation coefficient (R). *, ** and *** indicate the test significance at 95, 99 and 99.9%, respectively.



A significant correlation was found between the EC and the clay (r = 0.69), calcium (r = 0.67) and sodium content (r = 0.61), indicating that the use of these parameters as auxiliary predictors could improve the performance of the linear model applied, rather than just using the soil spectra data. Nawar et al. (2015) observed an increase in the estimation of soil electrical conductivity by almost 10% when soil clay content was combined with the reflectance values. Bilgili et al. (2011) also found an improvement in the accuracy of the CE estimation model when it combined with topographical variables (such as elevation).

Figure 2 shows the differences in the reflectance of the soil and sediment samples collected. It is believed that the greater humidity of the sediments, clay content and concentration of organic matter (Table 02) in relation to the soil resulted in a darker appearance of these samples, with a consequent uniform reduction in the reflectance of the incident radiation in the visible spectrum (Nocita et al., 2014; Weidong et al., 2002, Dalmolin et al., 2005; Moura-Bueno et al., 2020). Therefore, applying the indices and PLSR to each set of samples individually seemed relevant. In fact, the indices and PLSR proved to be more efficient when using only sediment spectral data (influence of higher reflectance) or the entire database (influence of the number of samples). According to the classification of Warrick and Nielsen's (1980), the coefficients of variation (CV) found for the EC and SOC parameters show the higher data variability (for both the soil subgroup, which may have influenced the better performance of the PLSR for those variables.

As expected, the results for the two hyperspectral satellites considerably exceeded those of Sentinel-2, showing that for estimating salinity and soil clay content, spectral resolution is more important than spatial resolution. It's important to highlight, the performance of the salinity indices in the satellite data was similar to that observed for the laboratory spectra. This similarity can be attributed to the use of laboratory data measured at different times and under different conditions, such as different operators, among other factors, which may have reduced their performance. In fact, when analyzing exclusively the spectral data collected during the current research (excluding the spectral library under construction by the research group), the salinity indices showed a slight improvement in performance ($R^2 = 0.94$). However, it is crucial to emphasize that the satisfactory results of the indices for the spectra obtained by satellite are extremely relevant, allowing for the precise mapping of salinity over large areas or in any location where satellite images are available. Comparing the two hyperspectral satellites, EnMAP showed slightly better accuracy than PRISMA, most likely due to the greater number of exposed soil and sediment pixels identified from the image of this sensor.

The soil attributes evaluated are essential when studying the feasibility of reusing sediment in agriculture. Firstly, classifying sediment as saline means that it cannot be reused, since high concentrations of salts inhibit plant growth (Braga et al. 2017, Canet et al. 2003). The organic carbon content reveals the presence of organic matter and nitrogen, increasing soil fertility (Capra et al. 2015). Lastly, sediments with higher clay contents contribute significantly to improving the physical structure of the soil, directly influencing cation exchange capacity, water retention and nutrients (Canet et al., 2003, Brigham et al. 2021, Kiani et al. 2021). In addition, this study shows the effectiveness of spectral indices and PLSR models in predicting these attributes from multi- and hyperspectral data, enabling medium- to large-scale mapping of these attributes. This step has proved fundamental to the practice of reusing sediments for agricultural production, since our previous studies have demonstrated the significant spatial variability of sediments in surface reservoirs. In addition, there is a dense network of reservoirs in the study area (with more than 1000 reservoirs larger than 5 ha) (Braga et al. 2019), making the task of sampling and laboratory analysis of the resource unfeasible.

However, the low performance of PLSR models for the spatial scale of data acquisition highlights the need to consider factors such as the limited amount of sediment pixels exposed in the available images, either due to the presence of clouds and/or vegetation, or even due to the reservoir being totally or partially full. These factors directly influenced the identification of reservoirs with sediment suitable for agricultural reuse, as initially planned. Obtaining future satellite images with a higher proportion of exposed sediment pixels is crucial to improving the accuracy of the models. The peculiar hydrological dynamics of the reservoirs in the study area (Braga et al. 2024) offer optimistic prospects for acquiring more adequate data in the short and medium term. To further optimize the application of the technique, it is suggested to continuously monitor and collect more samples in the watershed to obtain a more robust soil and sediment spectral library, improving the model's performance (Viscarra Rossel et al., 2016; Demattê et al., 2019; Moura-Bueno et al., 2020). Finally, it is also suggested that soil and sediment maps be drawn up separately (Naibo et al. 2022), as more sediment samples and satellite images become available, allowing for a more refined and accurate representation of the features under study.

4.6 Conclusion

The combination of reflectance spectroscopy with multivariate statistical techniques seems to be an effective approach for predicting electrical conductivity, organic carbon and clay content of soils and reservoir sediments in semi-arid regions. Better accuracy can be achieved if models are built for each environmental component individually. The prediction of salinity in both soil and sediment samples was most accurate using the ratio index (RI) model combined with the first derivative Savitzky-Golay preprocessing (FD-SG). On the other hand, PLSR models seem to be more suitable for predicting soil organic carbon and clay content, especially when no pre-processing of the spectrum is used. The mapping of those elements concentrations was a challenge due the lower number of bare soil/sediments pixels available by the multi and hyperspectral images. For this reason, future studies should look for images with less influence from cloud cover, water and vegetation. In addition, it is recommended that more soil and sediment samples be used in the construction of the models, thus increasing their accuracy.

5 FINAL CONSIDERATIONS

This study has provided valuable insights into the potential of sediment reuse from surface reservoirs in the Brazilian semiarid region as a sustainable soil conditioner for agricultural production. The exploration of sediment heterogeneity at a regional scale and its positive effects on maize growth and physiology underscore the viability of this practice as an alternative to high-consumption chemical fertilizers. The economic and environmental benefits, along with a thorough analysis of regulatory barriers, were systematically examined. Despite the challenges posed by the spatio-temporal variability of sediment characteristics, the frequent exposure of sediment in reservoirs and the absence of significant contamination risks suggest a feasible pathway for sediment reuse in agriculture. The focus on mapping physicochemical properties using advanced technologies such as multi- and hyperspectral data highlights the potential for predictive modeling, aiding in the effective implementation of sediment reuse. The combination of reflectance spectroscopy and multivariate statistical techniques emerges as a promising approach for assessing key soil parameters in semi-arid regions.

Building on the findings of this research, future studies could delve deeper into optimizing sediment reuse practices by addressing the identified challenges. Investigating the long-term effects of sediment application on soil health, crop productivity, and environmental impact would provide a more comprehensive understanding of the sustainability of this approach. Furthermore, expanding the geographical scope of the study to encompass diverse semi-arid regions and considering variations in climate and soil types would enhance the generalizability of the results. Investigating the socio-economic implications and acceptance of sediment reuse among local communities and farmers could contribute valuable insights into the broader feasibility and adoption of this practice. In light of the economic analysis conducted in the context of a global economic crisis, continuous assessments of the economic viability of sediment reuse, considering fluctuating market conditions, would be pertinent for practical implementation. Therefore, this study lays a foundation for future research endeavors aimed at advancing the understanding of sediment reuse in agriculture, contributing to sustainable practices, and addressing the challenges associated with its implementation on a broader scale.

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