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SEDIMENTS, SEC 5 • SEDIMENT MANAGEMENT • RESEARCH ARTICLE

Reuse of sediment as a soil conditioner in a semiarid region dominated by subsistence farming: sediment characterization at the regional scale and effects on maize crop

Brennda B. Braga[1,2] · **Carlos A. G. Costa**[1] · **Gabriela D. Lima**[1] · **Claudivan F. de Lacerda**[1] · **Saskia Foerster**[2] · **Arlena Brosinsky**[2] · **Pedro H. A. Medeiros**[3]

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Abstract

Purpose 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 deposited in surface reservoirs as a soil conditioner in a semiarid region, focusing on two features: the characterization of sediment physicochemical properties at the regional scale and the effect of the substrate containing sediment on the growth and physiology of maize.

Methods Sediment from the beds of 14 reservoirs was investigated, and two of them were used for the preparation of substrate for maize cultivation. Differences between the physicochemical properties of the sediments 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 ha^{-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.

Results 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 10 times higher in the sediment, compared to the soil, and the organic matter content was up to six times higher. In the plant experiment, the dose and source of the sediments influenced all of the analyzed variables. The addition of sediments to the soil increased the chlorophyll content, photosynthesis rate, and growth of the leaves in relation to the treatment containing only soil. There were no significant differences between the biomass production and the plants' nutrient extraction with the largest dose of the most enriched sediment when compared to the treatment with chemical fertilizer.

Conclusions The experiment of maize plant growth showed the feasibility of using sediment deposited in reservoirs as a 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

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 km^2. 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 2018) and rising prices of chemical inputs (Hassen and Bilali 2022), the use

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Extended author information available on the last page of the article 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. 2021), 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 km^2; 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 (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 are 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 maintaining 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 Material and methods

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 400 to 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).

The sediment sampling conducted in this study was preceded by the cleaning of the surface for litter removal. The

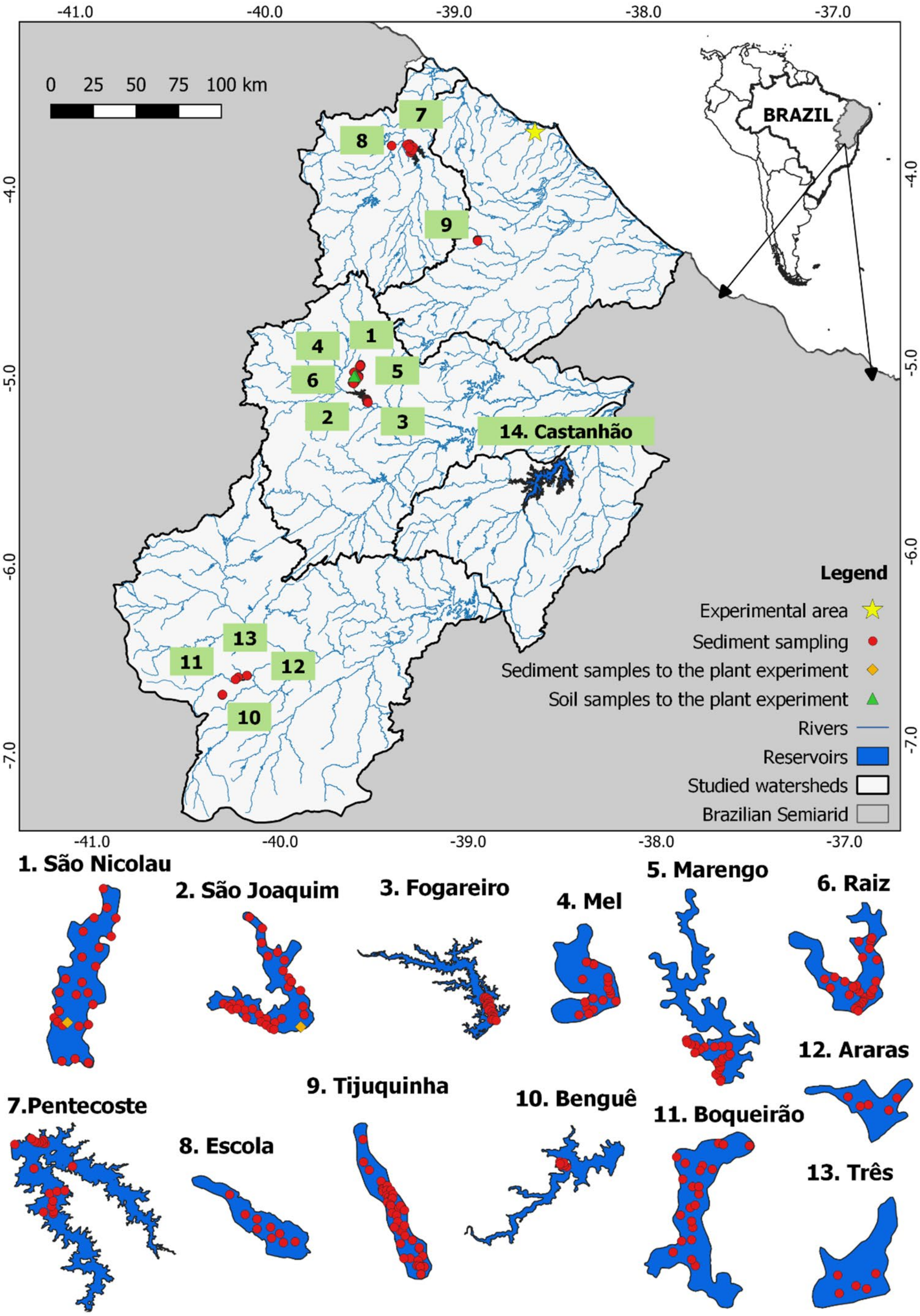


Fig. 1 Location of the study region and sediment sampling points

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), and most reservoirs (mainly small reservoirs) were 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.

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), and copper (Cu)—aluminum (Al), carbon (C), and organic

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

Reference	Watershed	Reservoir	RC	CS	NS	YS	EE
Brosinsky 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, and 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)	Medium 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, and 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, and granulometry
		São Nicolau	0.9	36.1	21		

RC reservoir capacity (hm^3), *CS* catchment size (km^2), *NS* numbers of samples, *YS* year of sampling, *EE* elements evaluated

*6 samples to N and 46 to O.M

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 described as follows: N soil content was performed using the Kjeldahl method, in which N is converted to ammonium sulfate through oxidation, and the released ammonia is determined by acidimetry; the P content 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 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 sulfate; 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 Reuse of sediment for maize cultivation

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.

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

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

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

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 °C, ranging from 29.1 to 43.9 °C.

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 et al. (2008).

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.

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

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

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

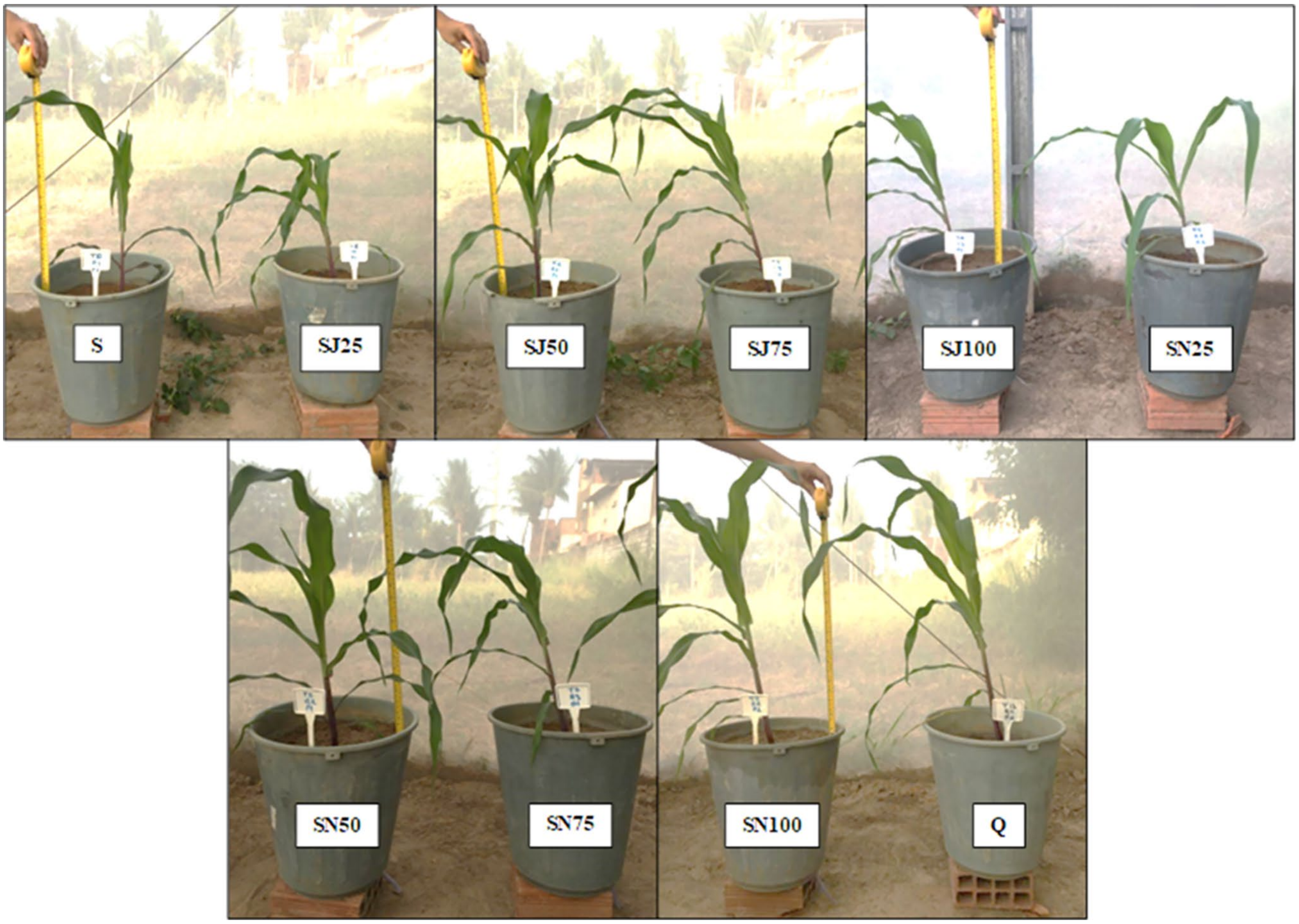


Fig. 2 Maize plants at 32 days after sowing (DAS) growing in substrates containing only soil (S), soil + São Joaquim's sediment (SJ), soil + São Nicolau's sediment (SN), and soil + chemical fertilizer (Q). The numbers 100, 75, 50, and 25 correspond to the sediment mass (in ton) per hectare

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 chlorophyll meter (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.

2.2.3 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 ($P \leq 0.05$).

3 Results and discussion

3.1 Physicochemical composition of sediments from surface reservoirs

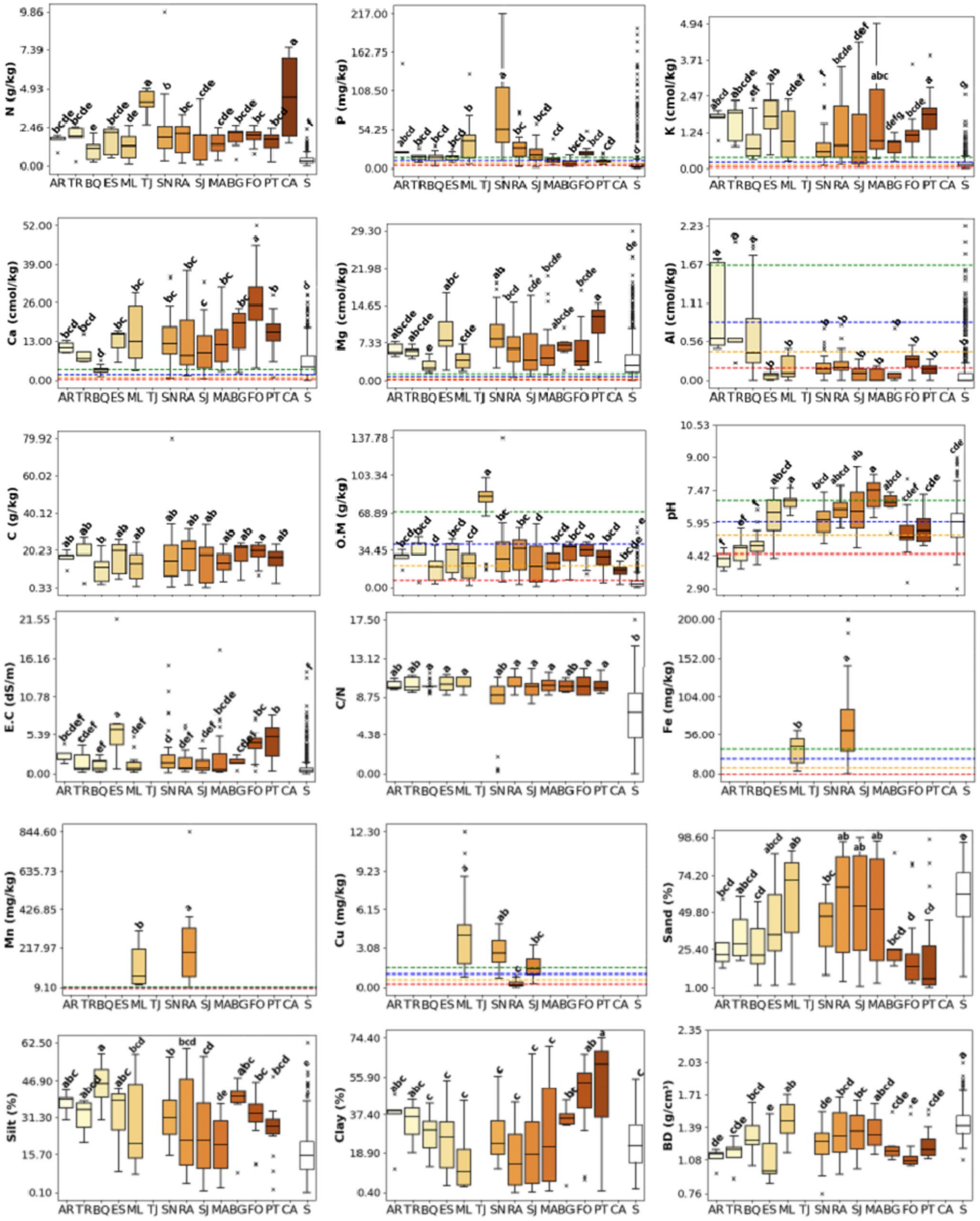
Based on the sediment database described in Sect. 2.1, we assessed the spatial variability of the sediment physical and chemical properties at regional scale and their heterogeneity (Fig. 3). To our knowledge, it is the largest sediment database for the study area containing around 280 sediment samples 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 showed that the sediment characteristics could not be clustered by the different basins.

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 (Brasil 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 and Wood 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).

Phosphorus 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).


N (g/kg)
9.86
7.39
4.93
2.46
0.00
P (mg/kg)
217.00
162.75
108.50
54.25
0.00
K (cmol/kg)
4.94
3.71
2.47
1.24
0.00
Ca (cmol/kg)
52.00
39.00
26.00
13.00
0.00
Mg (cmol/kg)
29.30
21.98
14.65
7.33
0.00
Al (cmol/kg)
2.23
1.67
1.11
0.56
0.00
C (g/kg)
79.92
60.02
40.12
20.23
0.33
O.M (g/kg)
137.78
103.34
68.89
34.45
0.00
pH
10.53
9.00
7.47
5.95
4.42
2.90
E.C (dS/m)
21.55
16.16
10.78
5.39
0.00
C/N
17.50
13.12
8.75
4.38
0.00
Fe (mg/kg)
200.00
152.00
104.00
56.00
8.00
Mn (mg/kg)
844.60
635.73
426.85
217.97
9.10
Cu (mg/kg)
12.30
9.23
6.15
3.08
0.00
Sand (%)
98.60
74.20
49.80
25.40
1.00
Silt (%)
62.50
46.90
31.30
15.70
0.10
Clay (%)
74.40
55.90
37.40
18.90
0.40
BD (g/cm³)
2.35
2.03
1.71
1.39
1.08
0.76
AR TR BQ ES ML TJ SN RA SJ MA BG FO PT CA S

◂**Fig. 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 $\alpha \leq 0.05$ 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)

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 (Tarnawski et al. 2015; Kiani et al. 2023), 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, and from 0.3 to 4.8 mg Cu per kg of sediment, values markedly lower than observed by other authors (e.g., Canet et al. 2003; Ebbs et al. 2006; Mattei et al. 2017; 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).

3.2 Effect of sediment as a 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 S1). 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).

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

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

Treatments	RCI	gs	A	Ci	E
	–	mol m^{-2} s^{-1}	μmol m^{-2} s^{-1}	ppm	mmol m^{-2} s^{-1}
S	30.7 b[a]	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

The values are represented by the averages

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

[a] Means followed by the same letter in the column do not differ by the Tukey test ($P > 0.05$)

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 and Lee 2020). 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 reduce 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).

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 photoassimilates 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.

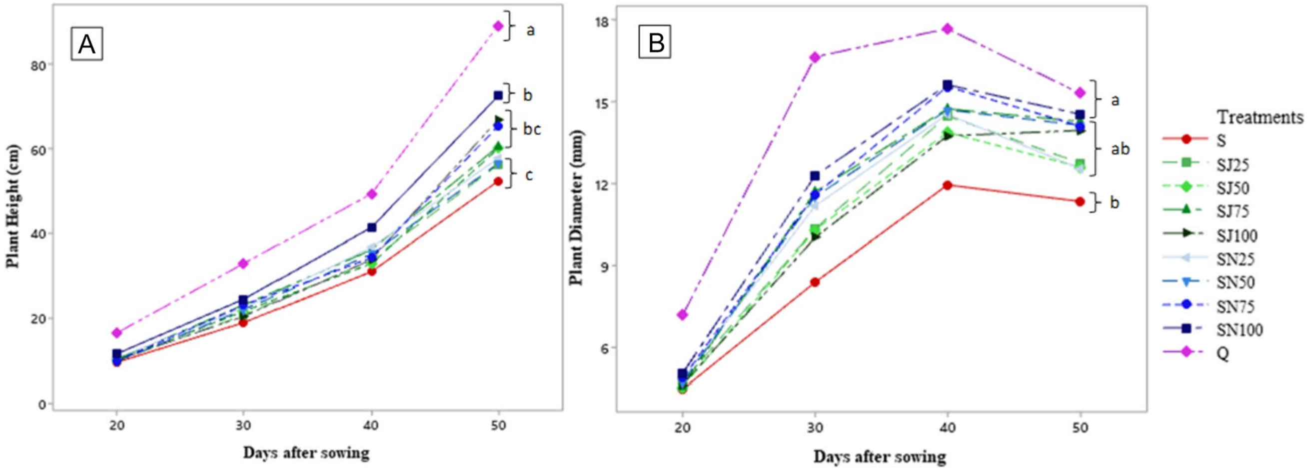


Fig. 4 Plant height (**A**) and stem diameter (**B**) of maize plants at 20, 30, 40, and 50 days after sowing (DAS) growing in substrate containing only soil, soil + São Joaquim's sediment, soil + São Nicolau's sediment, and soil + chemical fertilizer. The points represent the mean values of 8 repetitions. 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

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, the 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.

The 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 the 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 perenne 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 micronutrient 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,

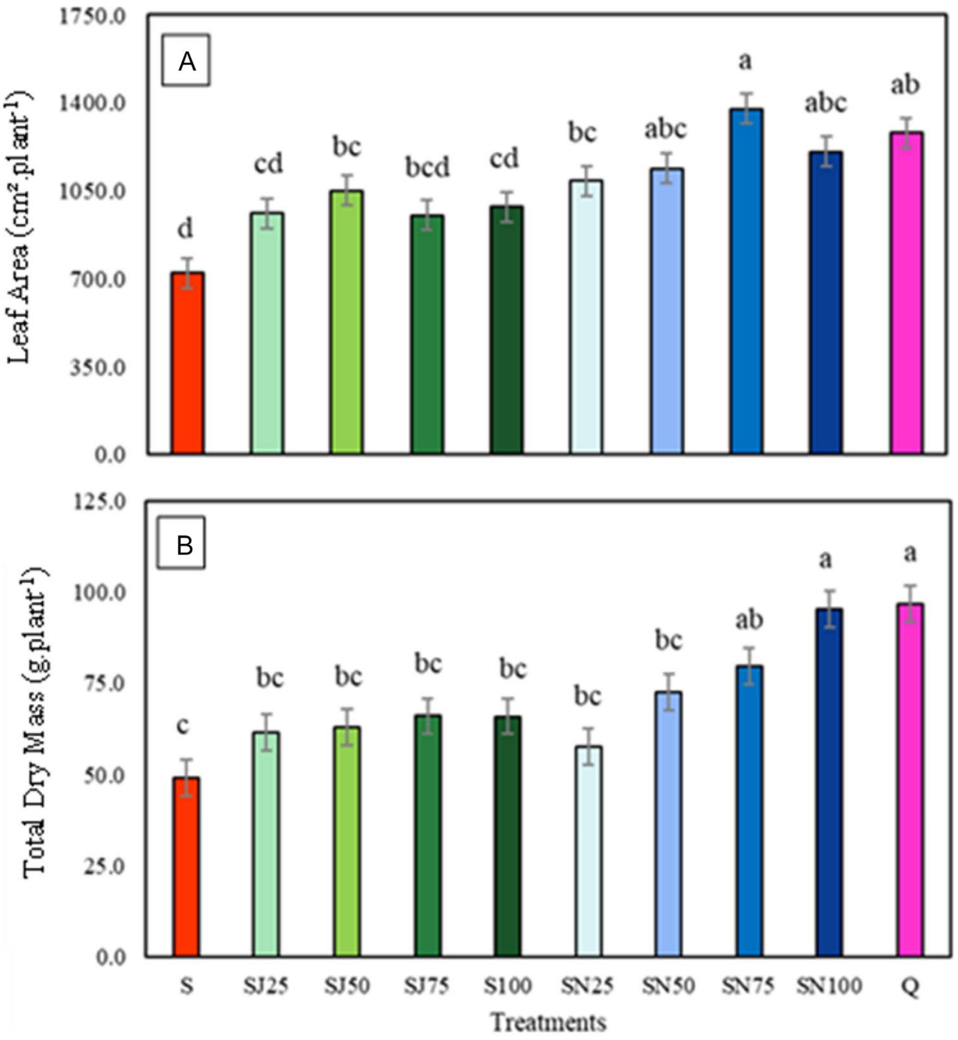


Fig. 5 Leaf area (**A**) and total dry mass (**B**) of maize plants at 96 days after sowing (DAS) growing in substrate containing only soil, soil + São Joaquim's sediment, soil + São Nicolau's sediment, and soil + chemical fertilizer. Values are represented by the mean ± standard error. Means followed 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

Mn, and Zn (Table S2). 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 and Marques 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.

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 was 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.

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

Treatment	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	g.plant^{-1}						mg.plant^{-1}				
S	0.34 c[a]	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

Values are represented by the mean

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

[a] Means followed by the same letter in the column do not differ by the Tukey test ($P > 0.05$)

In our previous studies in the semiarid region of Brazil (Braga et al. 2017, 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 the situation 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 analyses 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. 2009; 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).

4 Conclusion

The analysis of the physicochemical properties of the sediment showed the enrichment of nutrients, organic matter, and fine particles in this material. For instance, the concentration of N and K in the sediment was three to 10 times higher in the sediment (compared to soil) and the organic matter content up to six 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.

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Data availability Data will be made available on request.

Declarations

Competing interests The authors declare no competing interests.

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Authors and Affiliations

Brennda B. Braga[1,2] · Carlos A. G. Costa[1] · Gabriela D. Lima[1] · Claudivan F. de Lacerda[1] · Saskia Foerster[2] · Arlena Brosinsky[2] · Pedro H. A. Medeiros[3]

✉ Brennda B. Braga
braga@gfz-potsdam.de

[1] Department of Agricultural Engineering, Agricultural Science Center, Federal University of Ceará, Fortaleza-Ceará, Brazil

[2] Remote Sensing and Geoinformatics Section, Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany

[3] Federal Institute of Education, Science, and Technology of Ceará, Fortaleza-Ceará, Brazil