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SEDIMENTS, SEC 5 • SEDIMENT MANAGEMENT • RESEARCH ARTICLE

Reuse of sediments from surface reservoirs for agricultural production in the Brazilian semiarid region: extraction conditions, spatio-temporal variability, financial analysis and regulatory barriers

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Abstract

Purpose This study explores sediment reuse from surface water reservoirs as a soil conditioner to reduce reliance on chemical fertilizers. It considers the variability of sediment properties, the financial and environmental benefits and the regulatory barriers for adopting this practice, highlighting its potential for sustainable agricultural production.

Methods To assess the conditions for sediment extraction in the study area, we analyzed the temporal dynamics of water storage in 19 reservoirs. Spatio-temporal characterization of sediments was conducted using a database of over 200 samples from 10 reservoirs located in the Jaguaribe River Basin, in the Brazilian semiarid region. We also performed a cost-benefit analysis of sediment reuse in the context of the latest global economic crisis.

Results The temporal dynamics of reservoir water storage indicate frequent and prolonged sediment exposure, enabling removal by excavation. Sediment reuse can currently result in savings of up to 68% compared to conventional fertilization. Sediment heavy metals analysis showed that copper and zinc concentrations are, respectively, 4 and 35 times lower than the limits established by the most restrictive existing legislation. Replacing chemical nitrogen fertilizers with sediment could prevent nearly 12×10^3 t CO_2e emissions.

Conclusions Sediment reuse in agriculture can enhance crop yields and has the potential to substantially benefit both the environment and society. However, the spatiotemporal variability of the sediment's physicochemical properties may pose a challenge to scaling up this practice. While chemical fertilizer prices fluctuate, especially during global crises, sediment reuse costs remain more stable, providing financial predictability for the agricultural sector.

Keywords Sustainable agriculture · Food security · Nutrients cycling · Sediment reuse · Surface reservoir

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, while the sustainability of the agricultural sector has also been put to the test (Zou et al. 2022). Traditionally, growing demand for food has been met 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). Therefore, it is essential to develop strategies to promote more sustainable agricultural production, without losing efficiency.

According to Zou et al. (2022), the global application of phosphorus (P) fertilizers on croplands has already exceeded the estimated planetary limit, thus, it becomes

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increasingly important to close the agricultural P cycle. 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 keeping water quality at acceptable levels (Lira et al. 2020). Numerous studies suggest that bottom sediments from lakes can be used as a soil conditioner, by incorporating nutrients for agricultural production or as a supplement to chemical materials traditionally used for soil fertilization (Fonseca et al. 2003; Ebbs et al. 2006; Sigua 2009; Baran et al. 2012, 2019a; Braga et al. 2017; Tarnawski et al.). Sediment characteristics such as high contents of macronutrients in bioavailable forms, organic matter and fine soil fractions have been shown to improve the structure and sorption properties of soils (Canet et al. 2003; Tarnawski et al.; Renella 2021; Kiani et al. 2021), water-holding capacity and cation-exchange capacity (Brigham et al. 2021).

In semiarid regions such as the northeast of Brazil, peculiar conditions favor sediment reuse: (i) establishment of a network of surface reservoirs for water supply (de Araújo and Medeiros 2013) creates dispersed spots of sediment deposition that may be suitable for reuse; (ii) the occurrence of long periods of drought (Zhang et al. 2021) results in frequent reservoir drying, with large amounts of sediment becoming available for removal through cheap and easy excavation techniques. However, the benefits of using sediments in agriculture depend on their physicochemical (Braga et al. 2019) and ecotoxicological (Kiani et al. 2023) properties. As sediments can contain potentially toxic trace elements and organic pollutants at different levels (Baran et al. 2019b; Ferrans et al. 2019), it is mandatory to analyze their properties to assess the need for some treatment, management and potential applications (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).

Despite the challenges related to the sediment characteristics, its reuse in agriculture has been pointed out as an alternative source of nutrients and organic carbon to ensure global access to safe and sufficient food. However, food security is extremely affected by economic market and environmental limitations, such as climate change and water availability (Rad et al. 2021). For instance, the COVID-19 pandemic has caused damage to the global economy, as a result of lockdowns and the increased healthcare costs to control the disease (Meuwissen et al. 2021). In addition, consumers and producers have faced difficulties, such as the restrictions on imports and exports, that eventually led to a rise in fertilizer prices, reducing incomes for farmers, and impacting the agricultural sector, with short- and long-term effects on food security around the world (Rivington et al. 2021).

In this study we explore 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. The analysis included: (1) assessing temporal changes of sediment characteristics by re-sampling and analyzing sediment from previously sampled locations (5 years later); (2) updating our cost-benefit analyses with respect to current price developments and the impact of the global fertilizers market; (3) assessing legislation on different aspects related to sediment excavation, application and contents, such as nutrients and contaminants; and (4) modeling the mass of sediment - and associated nutrients - deposited annually in the reservoir network. In addition, we highlight some potential beneficial aspects of the practice with respect to carbon footprint and the development of a tool that makes the findings of our scientific research more accessible to small farmers in the study region.

2 Materials and methods

2.1 Study area

The Jaguaribe River Basin (JRB) covers more than 75,000 km² in northeastern Brazil (Fig. 1a) and 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% occurring from January to June (Alves et al. 2012). A notable characteristic of the Jaguaribe River is the high variability of inter-annual and intra-annual river discharges: within a short period of time, the Jaguaribe streamflow can vary from 7,000 $m^3\ s^{-1}$ to zero (Campos et al. 2013). The geology of the JRB is predominantly composed of crystalline complexes (85% of the area), with few sedimentary areas (15%), and therefore groundwater is limited and mainly concentrated in fractured aquifers. The predominant soils are ferralsols, luvisols, and acrisols (COGERH 2009).

The high spatiotemporal variability of precipitation and a predominance of soils and geology with low water storage capacity motivated the implementation of a dense network of dams for water supply in the study area (de Araújo and Medeiros 2013): more than 3,000 reservoirs with surface areas larger than 5 ha (Pekel et al. 2016) were identified in the basin. Most of the dams, particularly the small ones, were built spontaneously by the rural population as an adaptation to droughts (Pereira et al. 2019) and constitute a crucial coping measure for the livelihoods of communities

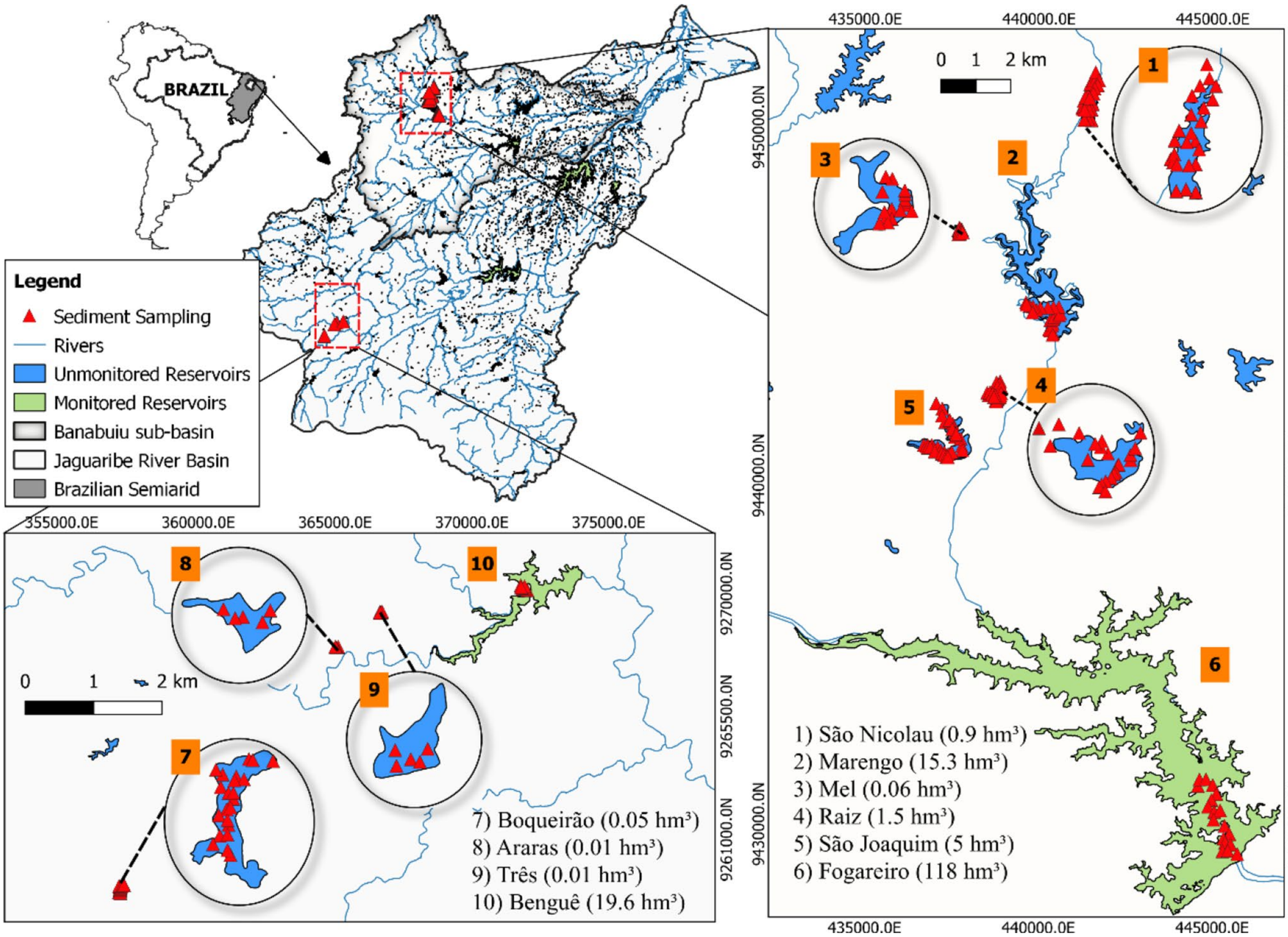

Fig. 1 Location of the study area in the Jaguaribe River Basin, Brazilian semiarid region. The map highlights the reservoirs where sediment samples were collected

living around these structures (Medeiros and Sivapalan 2020), although not monitored by the water management company. These small reservoirs play a social role in promoting spatial distribution of water, allowing remote rural populations to have access to the water system and improving their quality of life. The reservoir network also enhances energy efficiency (Nascimento et al. 2019), since the center of gravity of the available water is higher than it would be without the network. The Banabuiu sub-basin represents 30% of the JRB and also has a large number of small and unmonitored reservoirs (about 1 reservoir per 6 km²) (Braga et al. 2019), indicating a lack of observational data on the water dynamics and stored water volume in these water bodies. Regulatory agencies monitor the volume of only 19 large/medium-sized reservoirs. Therefore, the analysis of sediment extraction conditions (topic 3.1) was based on data from the monitored reservoirs in this catchment (Fig. 1).

2.2 Accessibility for sediment extraction in the Banabuiu catchment

To demonstrate the hydrological behavior of the study region, water storage data since 2004 from nineteen monitored reservoirs in the Banabuiu catchment (Fig. 1) were assessed (COGERH 2023). The data are made available by the Water Resources Management Company of Ceará (COGERH) and the Foundation of Meteorology and Water Resources of Ceará (FUNCEME), on the Ceará State Hydrological Website (http://www.hidro.ce.gov.br/), and have been essential for understanding the hydrological dynamics of reservoirs located in the basin, particularly during droughts, when bed sediments are exposed and become accessible for excavation.

2.3 Sediment database and Spatiotemporal variability of sediment properties

In this study, we used a database consisting of the results from several sediment sampling campaigns conducted by our research group since 2013. These campaigns covered a vast study area, involving more than 200 sampling sites distributed in 10 selected reservoirs in the Jaguaribe River Basin (Fig. 1). The objective of this systematic sampling was to gain a comprehensive representation of the sediment characteristics in the investigated reservoirs, as well as to identify potential limitations of sediment reuse as a soil conditioner. The data obtained in these campaigns provide a solid basis for the analysis and understanding of hydro-sedimentological processes and are essential for assessing the feasibility of sediment reuse in small-scale agriculture in the Brazilian semiarid region. Details on sediment sampling and analysis are reported by Carvalho et al. (2022) and Braga et al. (2023).

To assess temporal changes in the physicochemical properties of sediments, we compared the results of "sediment samples collected at the same sites during two campaigns conducted five years apart (in 2016 and in 2021), at the São Joaquim and São Nicolau reservoirs (reservoirs 1 and 3 in Fig. 1). During this period, the reservoirs fluctuated between nearly empty and partially flooded. Sentinel-2 satellite images from November (when cloud-free images were made available) of each year between 2016 and 2021 were used to analysing the evolution of the reservoir inundation areas. A one-way ANOVA at a significance level of 0.05 was performed to determine whether the temporal changes in the physicochemical properties of the sediments were statistically significant.

2.4 Financial analysis of the sediment reuse practice

To assess the financial feasibility of the sediment reuse technique for soil fertilization, its temporal variability and vulnerability to the fertilizer market, an update of fertilization costs (CONAB 2021) presented in our previous study (Braga et al. 2019) was conducted.

The costs associated with sediment reuse consist primarily consists of physicochemical laboratory analysis, excavation from the reservoir bed and transport to the crop field (including equipment rental, fuel and operation). In the study area, the Infrastructure Secretariat of Ceará State (SEINFRA/CE) presents reference values for the excavation and transport of soils for public works, which, for the Banabuiu catchment (where the average sediment transport distance is 2.3 km) is US$ 3.15 m^{-3} (Braga et al. 2019). The volume of sediment required to fertilize the soil depends on the concentrations of the reference nutrient in the soil and the sediment (Table S2) and the crop requirements (Table S1). In our study, we computed the nutrient budget based on nitrogen concentrations and maize cultivation. Furthermore, we included the cost of environmental permitting for reservoir desilting in this study.

On the other hand, the costs of conventional fertilization mainly consist of fertilizer purchase, which is influenced by the market dynamics and supply chains, and the transportation costs of the chemical fertilizers, which are regulated by the Brazilian Transportation Agency (Resolution No. 5820/2018). Table 1 summarizes the cost evolution of the two techniques (conventional fertilization and sediment reuse) from 2019 to 2023, relative to 2018 values. In Supplementary Material (Table S3), the detailed costs of each technique between 2018 and 2023 are shown.

2.5 Legislation on sediment reuse in agriculture

Despite numerous studies on sediment reuse applications, there is a legislative gap in regulating the practice in the agricultural sector (EU 2019; Macci et al. 2022). In the Brazilian semiarid region, growing crops on the beds of empty reservoirs– known as 'vazante' (de Araújo 2004) - is a traditional practice among the local population, however there is still no specific legislation regulating the removal of sediments and their use for soil fertilization, which leads to the misuse of this resource. Across several EU countries, which collectively produce around 200 million m³ of sediment per year removed from various waterbodies (Macci et al. 2022), different approaches to classifying sediment quality are being developed (Heise 2018). Finland, Slovakia and the Czech Republic, for instance, have established contaminant

Table 1 Increase of the costs of conventional fertilization and sediment reuse from 2019 to 2023 in relation to 2018

Technique	Product/ service	Price increase (%) in relation to the year 2018				
		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 limits for direct use of this material. Given this scenario, we compared the zinc and copper content in sediments from our database with contaminant limits established by existing legislations (Kiani et al. 2021; Macci et al. 2022) and the threshold values for sediment disposal in soils according to the Brazilian legislation (CONAMA 2012).

2.6 Availability of macronutrients in sediments from surface reservoirs

The mass of macronutrients (N, P and K) in the sediment from surface reservoirs was calculated annually for the Banabuiu catchment and the JRB, as the product of the annual mass of silted sediment and the mean nutrient content, computed from our database. To estimate the mass of silted sediment in surface reservoirs located in the Banabuiu catchment and JRB, we scaled up the methodology from our previous study (Braga et al. 2019), which used the model proposed by Lima Neto et al. (2011) (Eqs. 1 and 2):

$$\Delta M_j = V_{o,j}\xi_m R_j \quad (1)$$

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

Where ΔMj is the total mass of sediment retention in each reservoir (t $year^{-1}$), $V_{o,j}$ is the initial storage capacity of the reservoirs (m^3), ξ_m is the rate of sediment retention (equal to 3.65×10^{-7} t m^{-3} MJ^{-1} mm^{-1} ha h in the study region, according to the authors) and R_j is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1}), estimated for the Brazilian semiarid region based on monthly averages (Pm) and total annual (P) precipitation (mm).

The aforementioned method was applied to each reservoir and the total sediment retention at the two scales, i.e., the Banabuiu catchment and JRB, was computed as the sum of the mass of sediment retention in all reservoirs. It is important to note that only sediments from non-strategic surface reservoirs, i.e. those not monitored and managed by COGERH, with flooded areas larger than 5 hectares were considered, because large strategic reservoirs have certain limitations for adopting this practice: as they are used for human water supply, therefore no operations are allowed in these reservoirs; additionally, such reservoirs are managed to prevent complete emptying, meaning that sediment is not exposed as in smaller ones. The nutrient content in the sediment was assumed to be the mean value of each nutrient (N, P and K) from the sediment samples in our entire database (see Sect. 2.2) at each scale.

3 Results and discussion

3.1 Accessibility for sediment extraction in the Banabuiu catchment

The temporal dynamics of water storage in the 19 monitored reservoirs of the Banabuiu catchment are presented in Fig. 2. Note that reservoirs with larger capacities, such as Fogareiro (see Fig. 1), require longer periods after droughts to recover substantial accumulated volumes. On the other hand, the smaller ones present a much more intense filling and emptying dynamic, as observed in the Jatobá and São José I reservoirs. Extended droughts, such as the period from 2012 to 2018, may cause significant changes in the water balance of small reservoirs, leading to conditions in which they remain empty (or partially empty) during the recharge period (Zhang et al. 2021). Thus, bottom sediment in small reservoirs is exposed with relatively high frequency and can be advantageously removed by excavation. Excavation is cheaper and faster than other sediment removal techniques, such as dredging, which makes it a more feasible solution for farmers with limited resources. Furthermore, dewatering the sediment before its application to the soil is not required, further reducing the costs of the sediment reuse technique. According to Moog et al. (2018), although sediment removal by excavation may reduce benthic invertebrates' biomass by 82%, the fauna in the affected area is expected to return to pre-operation conditions in approximately 235 days. In the study region, Fig. 2 suggests that the reservoirs may take longer than this interval to refill after becoming empty and exposing sediments for removal.

3.2 Spatiotemporal variability of sediment properties

The ANOVA for different periods of physicochemical characterization of sediments from São Nicolau (Fig. 3) showed that fluctuations in the reservoir from 2016 to 2021 were statistically insignificant (p-value $>$ 0.05), except for Na, C and N. Overall, the highest levels were recorded in 2016. On the other hand, in the São Joaquim reservoir, only the K averages showed statistical differences between years, with higher values observed in 2021, except at point SJ05 (Fig. 4). The F and p-values from the ANOVA for each analyzed parameter are presented in the Supplementary Material (Table S4).

This result may be linked to the prolonged drought that affected the region from 2012 to 2017 (Zhang et al. 2021), leading to the accumulation of nutrients in the sediment. However, from 2018 to 2021, rainfall remained within the historical average for the region, and the reservoirs were partially filled (Figs. 3 and 4 show the evolution of the

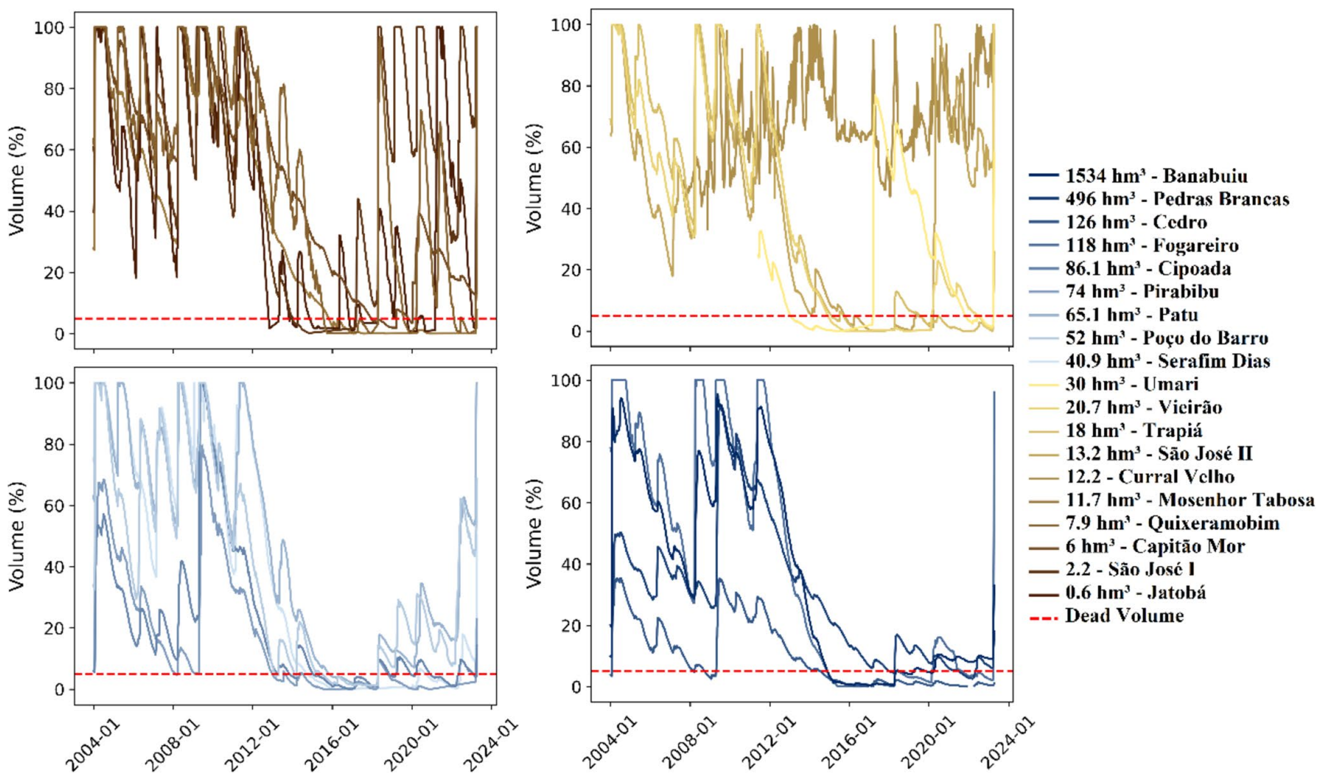

Fig. 2 Temporal water storage dynamics of the monitored reservoirs between 2004 and 2013 in Banabuiu catchment, indicating the frequency with which the reservoirs' sediments are exposed and available for extraction. The line color indicates the reservoir capacity from small (brown) to large (blue). The red dashed lines represent the dead volume threshold

flooded area of the reservoirs over time). As water levels rose, nutrients were likely transferred from the sediment to the water column (see, for instance, Lima Neto et al. 2022). Furthermore, nutrients may have been absorbed by aquatic plants for biomass growth (Kalengo et al. 2021) or removed from the system during water withdrawal. On the other hand, since points SN05 and SN03 are farther from the dam and located in areas not submerged during the analyzed period, there was an even higher accumulation of nutrients at those points. Some circumstances may have caused this result, such as crop cultivation on the reservoir's banks (Fig. 5A-B) and extensive livestock farming in the surrounding areas (Fig. 5C-D), as nutrients from animal waste accumulated in the soil can be transported by surface runoff. It is important to note that there is no large-scale agricultural production or livestock grazing in the reservoirs' catchments, nor are there industrial facilities nearby; therefore, pollution originates from diffuse sources in São Nicolau and São Joaquim. According to Leip et al. (2015), livestock farming is one of the most significant anthropogenic sources of nutrient input to surface waters. We also assume that the analyzed time window (5 years) is insufficient to detect significant changes in the physicochemical properties of the sediments. Ebrahimi et al. (2023) did not observe significant variations in phosphorus concentrations across the four seasons in the sediments of the southern Caspian Sea.

3.3 Financial analysis of the sediment reuse practice

Various technical solutions are available to manage 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 increased consumer demand for organic food may influence the use of chemical fertilizers (Nikaflar et al.). In this context, sediments can function 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.).

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

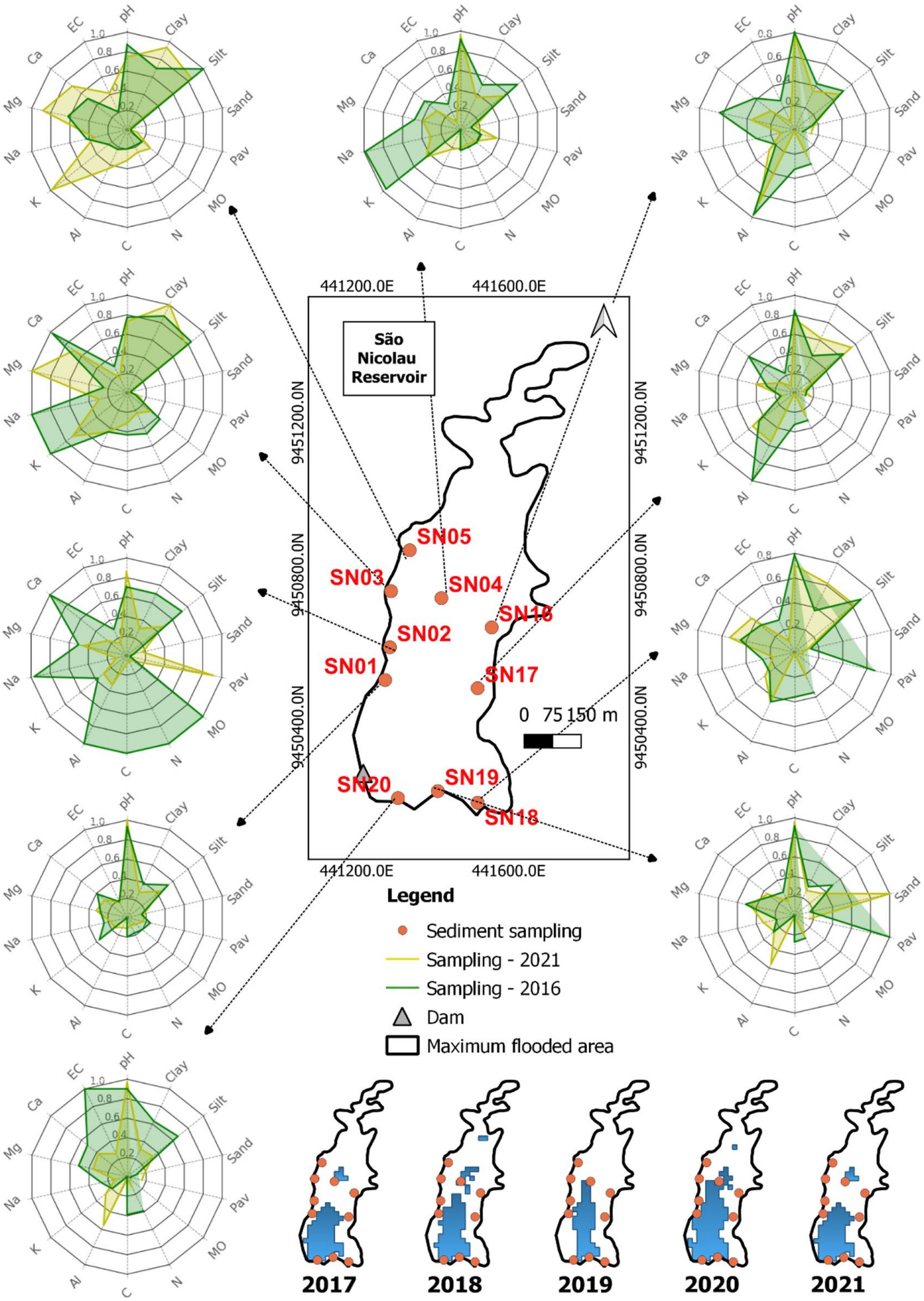

Fig. 3 Spatio-temporal assessment of the physicochemical properties of sediments from São Nicolau reservoir. The values were normalized by the database maximum value to be presented on the same scale. The temporal evolution of the reservoir flooded area is represented at the bottom by Sentinel-2 satellite images in blue. Legend: Pav - available phosphorus; EC– electrical conductivity; MO - organic matter

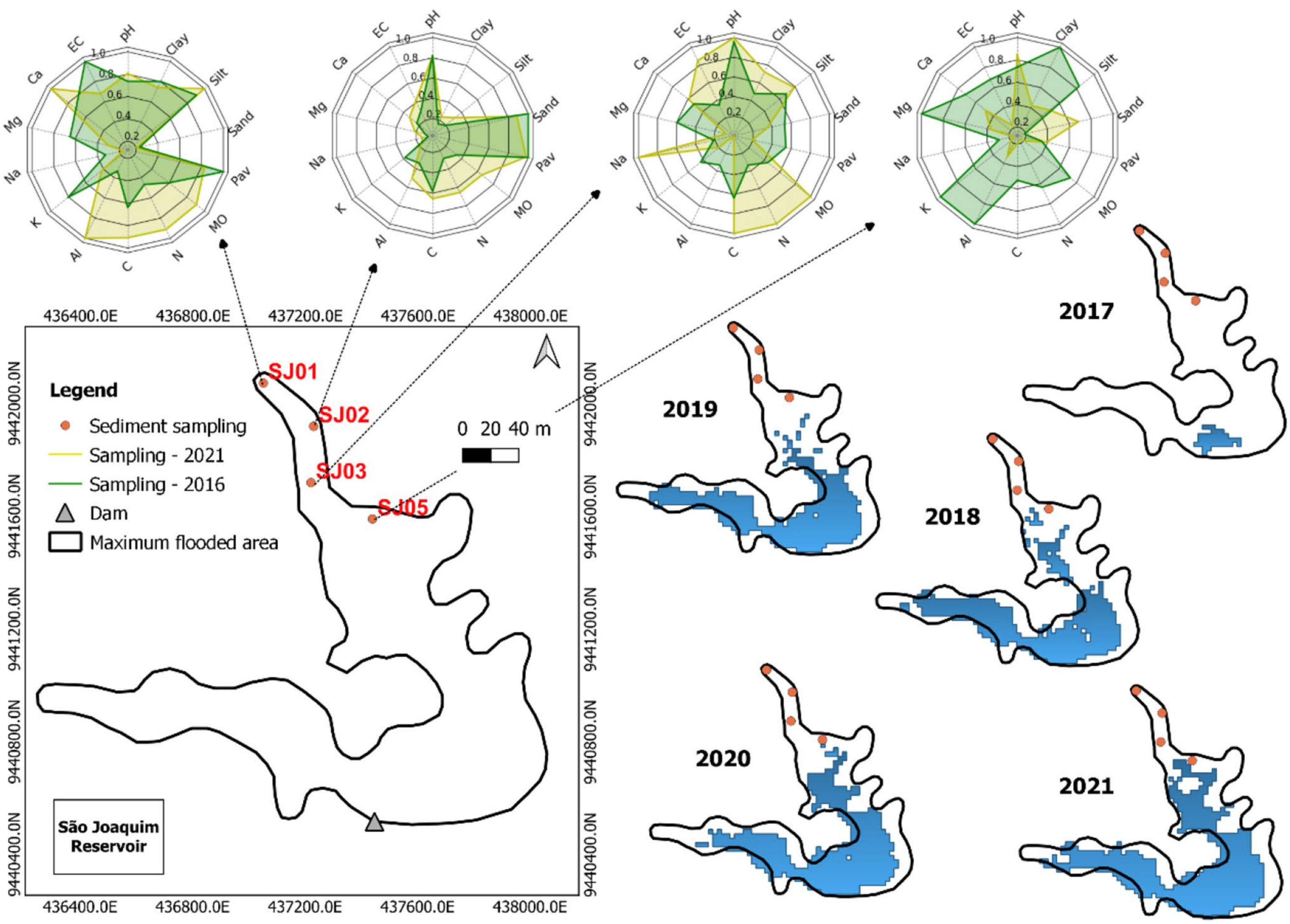

Fig. 4 Spatio-temporal assessment of the physicochemical properties of sediments from São Joaquim reservoir. The values were normalized by the database maximum value to be presented on the same scale. The temporal evolution of the reservoir flooded area is represented at the bottom by Sentinel-2 satellite images in blue. Legend: Pav - available phosphorus; EC– electrical conductivity; MO - organic matter

in the sediment, this practice could increase the costs compared to conventional fertilization.

Fertilization costs vary over time, for example, due to changes in the global food market (Hassen and Bilali 2022) and/or availability of chemical fertilizers, whereas sediment reuse costs tend to be more stable. Figure 6 presents the results of the financial analysis for soil fertilization for the period 2018–2023. With the inclusion of the environmental permit costs for reservoir desilting (a mandatory step in the study region) in the values calculated by Braga et al. (2019), the sediment reuse costs, except for the Marengo reservoir, became of the same order of magnitude as conventional fertilization between 2019 and 2020 (Fig. 6). It is important to note that indirect benefits, such as the recovery of the reservoir's storage capacity and improvement in water quality (with reduced costs for water treatment) are not considered in this analysis. However, since 2021, conventional fertilization costs have risen markedly, and with these increases being far more significant than the rise in factors influencing sediment reuse costs. Among chemical fertilizers, K has shown the highest variation, reaching up to 316% above 2018 levels (Table S1). Thus, using sediment as a nutrient source in agriculture reduces the costs in all scenarios and enhances the predictability of agricultural production.

In the specific period assessed by us (2018–2023), the COVID-19 pandemic and the war in Ukraine disrupted several supply chains and logistics worldwide, affecting fertilizer prices (Rice et al. 2022). According to Wang et al. (2018), supply-demand balance, weather conditions, production costs and trade flows are some of the factors influencing the fertilizer market. It is important to note that the mineral fertilizer supply is geographically concentrated and controlled by a small number of companies and countries (Hassen and Bilali 2022). For example, Russia and Belarus account for one-third of potash fertilizer exports global, thereby influencing its price (Benton et al. 2022). Moreover, Russia is currently the world's leading exporter of nitrogen fertilizers. The production of these fertilizers relies on natural gas as a raw material, whose price rose significantly in 2021, when nitrogen fertilizer prices reached

Fig. 5 Land use near the reservoirs. In **A** and **B**, bean and grass cultivation around the sediment sampling points in the São Joaquim reservoir. In **C** and **D**, livestock farming along the banks of the São Nicolau reservoir, where cattle also frequently access the lake directly for drinking water

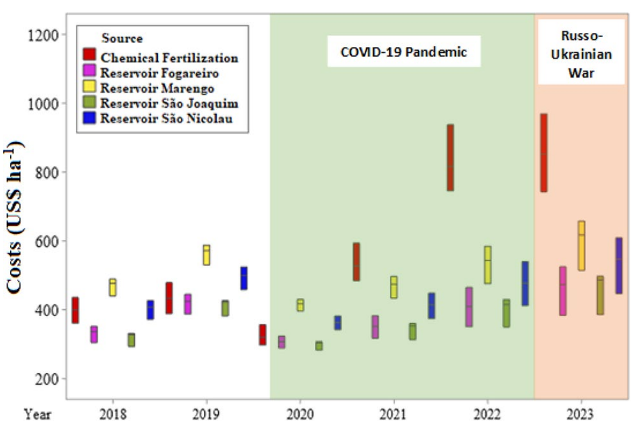

Fig. 6 Temporal variation (2018–2023) of the costs of conventional soil fertilization and sediment reuse to meet the nutritional requirement of maize. FO, MA, SN and SJ refer to the sediments from Fogareiro, Marengo, São Nicolau and São Joaquim reservoirs, respectively. All values obtained in Brazilian 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$−1, from 2018 to 2023, respectively

their highest level since 2010. Regarding phosphorus-based fertilizers, prices have also been affected by export restrictions resulting from domestic trade policy measures. For instance, China, a major producer and supplier of phosphate fertilizers, chose to limit its exports between July 2021 and June 2022 to secure domestic supplies (Benton et al. 2022).

To understand the overall impact of fertilizer prices on global food security, it is essential to acknowledge the long-term and large-scale consequences 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 the consequences of the recent crisis was observed in Brazil: one of the alternatives proposed was to open potash mining areas in 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 nutrient sources for the agricultural sector can be a potential alternative to ensuring agricultural productivity, especially for small farmers, who are financially more vulnerable.

3.4 Legislation on sediment reuse in agriculture

Analysis of the legislation applicable to sediment reuse in agriculture included the existing relevant legislation in Brazil (Sect. 3.4.1) as well as other parts of the world

(Sect. 3.4.2), and suggested steps for regulating sediments reuse for agricultural purposes (Sect. 3.4.3).

3.4.1 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), economic (potential to reduce production costs) and ecological (nutrients recycling) reasons. However, sediments are heterogeneous and may contain elements such as heavy metals, organic contaminants and pesticides (Canet et al. 2003), which could prevent their use in agriculture. The land use from which the sediment originates, as well as remediation measures of soil degradation, are factors that determine the presence, absence and concentrations of contaminants (Macci et al. 2022).

Sediments from shallow lakes and artificial reservoirs, located far from urban centers are usually considered low-risk sources of heavy metals and other contaminants, as these water bodies 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 water residence time, meaning that any contaminants entering the system are unlikely to accumulate to high levels over time (Moura et al. 2020). In this study, the reservoirs are located in rural areas with no industrial activity or large agricultural fields nearby, where small-scale family farming predominates (Braga et al. 2023). Therefore, sediments extracted from such water bodies may not require the same level of analysis as those from potentially polluted regions.

In this context, one approach to assessing the safety of using sediment for agricultural purposes is to adopt the maximum contaminants limits allowed in fertilizers and/or agronomic substrate for plants, as established by the Brazilian Secretary of Agriculture (BRASIL 2016). However, our database does not include the contaminants listed in this regulation: arsenic, cadmium, lead, mercury, chromium, nickel and selenium).

Additionally, the Brazilian National Environmental Council, through Resolution No. 454/2012, established guidelines and procedures for managing sediments from water bodies under national jurisdiction (CONAMA 2012). This regulation considers the disposal of dredged sediments on soils for agricultural purposes as a potential 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 for reuse as a nutrient source for plants. The sediments assessed in our study exhibited trace element contents markedly lower than the alert limits (Fig. 7), indicating that, despite the sediment heterogeneity, its use for agricultural purposes should be safe.

Although the analysis of sediment originating from reservoirs in the Brazilian semiarid region may not be mandatory to detect contamination by trace elements, it remains an important step for assessing overall sediment quality and identifying potential limitations to its reuse in agriculture. In addition to trace element content, sediment application may increase their concentrations in plants (Tarnawaski et al.; Baran et al. 2019a; Szara-Bąk et al.), depending on the type and dose of sediment applied (Kazberuk et al. 2021). 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. These elements were not analyzed in our study due to the financial constraints and the low probability

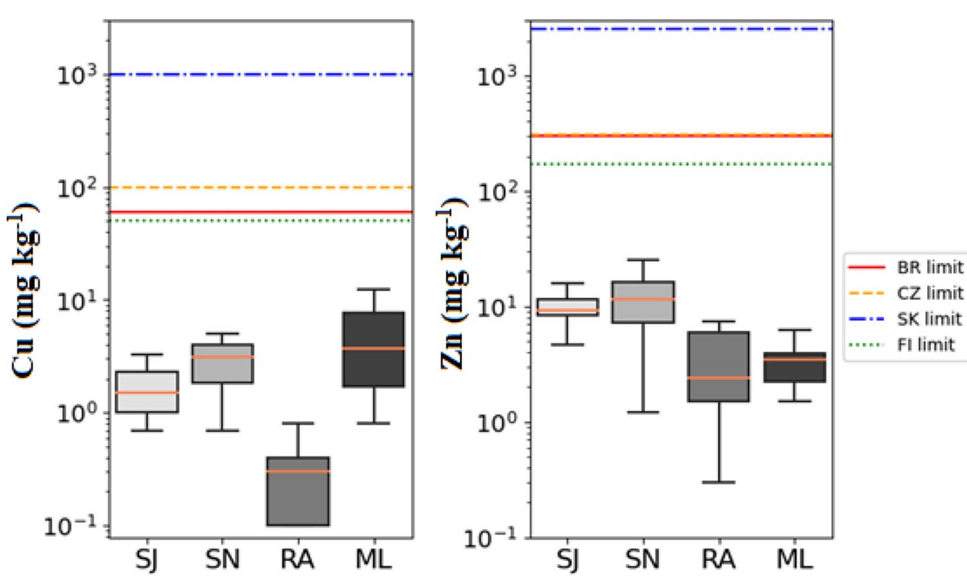

Fig. 7 Copper (Cu) and Zinc (Zn) concentrations in the sediments from São Joaquim (SJ), São Nicolau (SN), Raiz (RA) and Mel (ML) reservoirs. The lines represent the limits established for the disposal of sediments in soil by Brazilian legislation (BR) and direct reuse in agriculture by Slovakian (SK),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

of anthropogenic contamination in the bottom sediments of the studied reservoirs. We recommend that future studies include these and other potentially toxic elements (e.g., Ba, Cu, Hg, Ni, Se, Sb, Zn), particularly in regions with higher contamination risks, such as areas influenced by mining, industrial or intensive agricultural activities.

3.4.2 Legislation in other countries

Currently, the reuse of sediments in agriculture has gained significance, as numerous countries seek alternative nutrients sources that are less dependent on the fertilizer market and have lower environmental impacts (ESPP 2023). The feasibility of using sediments as fertilizers could be a key factor in addressing global food security issues (Szara-Bąk et al.). The analyses of Copper and Zinc in the sediment from the studied reservoirs showed that the concentrations of these elements are well below the maximum limits allowed by existing regulations in other countries for the direct reuse of sediment in agriculture (Fig. 7). The highest concentrations of zinc and copper were 12.1 and 4.8 mg kg^{-1}, respectively, which are 4 and 35 times lower than the limits set by the most restrictive legislation (Finland regulations).

Szara-Bąk et al. () observed similar results regarding copper and zinc content in the bottom sediments of Rożnów reservoir. Macci et al. (2022) also reported zinc and copper concentrations within these limits in saline-remediated and brackish sediments. Baran et al. (2019a), working with bottom sediments from a reservoir used for water supply, located in an urban development area in Poland, observed zinc and copper concentrations much higher than those measured in our study, but still below the established limits. However, Nin et al. (2022), working with treated sediment from an urban port, and Leue and Lang (2012), analyzing sediments from an urban channel, found high concentrations of heavy metals. In Sweden, the ratio between cadmium and phosphorus content is the key parameter in regulations governing the possible use of sediments in agriculture (Djerf and Ferrans 2022). In Poland, sediments reuse is legally accepted only if it is proven that the sediments are classified as non-hazardous (EU 2008).

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

In Brazil, another existing regulation should also be considered for the governance of sediment reuse: the environmental permitting process for reservoirs desilting. This regulation applies to the final stage sediment removal from reservoir beds and depends mainly on the characteristics of the water body. For instance, if the desilting area is less than one hectare, only a simplified environmental permitting process is required. Full compliance with all the regulations mentioned could serve as a starting point for establishing sediment reuse polices in Brazil, thereby ensuring its sustainable utilization by the agricultural sector (Fig. 8).

To ensure the safe and responsible use of sediment as a nutrient source for plants, either as an alternative or a complement to chemical fertilizers, it is important to develop specific regulations with clear guidelines for its application in agriculture (Macci et al. 2023). Promoting the use of uncontaminated sediment helps prevent its disposal, aligning with the new EU regulations on fertilizers (Renella 2021). These regulations should also set procedures for monitoring its application 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).

3.5 Sediment reuse in agriculture: towards a more sustainable crop production

The main benefit of reusing sediments for soil fertilization is reducing the use of chemical fertilizers. By applying the reservoir siltation model proposed by Lima Neto et al. (2011), we estimated that approximately 2×10^6 t of sediment are deposited annually in the nearly three thousand non-strategic surface reservoirs larger than 5 ha in the Jaguaribe River Basin. In our previous study (Braga et al. 2023), we reported the variability of macronutrient content in the sediments of reservoirs studied in the JRB and the Banabuiu sub-basin. Considering the average nutrients content in sediments and the sediment deposition rate, we estimated the available mass of NPK. Sediments from the Banabuiu catchment accumulate approximately 1039 t of N, 25 t of P, and 266 t of K per year (Fig. 9). Scaling those values up to the Jaguaribe River Basin, despite the slightly lower average nutrient concentration in the sediment of the reservoirs in this larger area, we estimate approximately 3347, 52 and 867 t of N, P and K, respectively. By applying this approach, we assumed that the nutrient content in the sediment is temporally constant. However, in this same study, we acknowledge that the physicochemical properties of the sediment vary over time. Since it was not possible to identify a clear temporal pattern for the macronutrients in the sediment - at least within 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 limitation of our estimation. When compared to chemical fertilizers, these results suggests that sediments deposited in surface reservoirs in the JRB could potentially replace approximately 7437 t of urea (45% of N), 259 t of simple superphosphate (20% of P) and 1444 t of potassium chloride (60% of K).

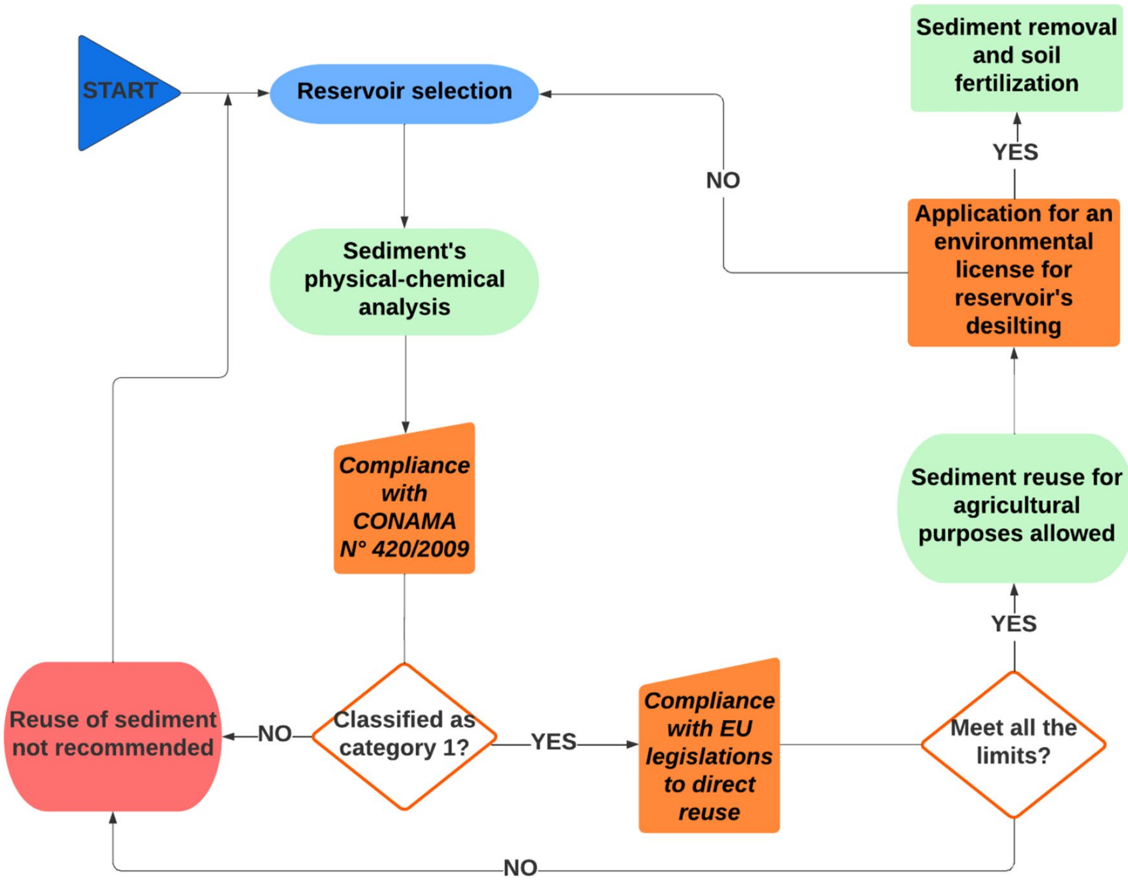

Fig. 8 Proposed steps for regulating sediment reuse for agricultural purposes in Brazil. Category 1 (CONAMA 420/2019): soils (or sediments, in this context) with concentrations of chemical elements equal to or below the established reference values

The partial replacement of chemical fertilizers with sediment reuse has the potential to reduce the carbon footprint of the agricultural sector. For instance, the chemical N fertilizer supply chain released into the atmosphere 1129.1 ± 171.1 t CO_2e in 2018 (Menegat et al. 2022). This value accounts for GHGs emissions from manufacturing, transporting and subsequent direct and indirect soil emissions resulting from fertilizer application on agricultural lands. Production and transportation alone are responsible for 41.4% (0.48 G t CO_2e) of global GHG emissions from synthetic N fertilizers. Furthermore, according to Bentrup et al. (2018), in 2014, the reference value for urea carbon footprint in Latin America was 1.7 t CO_2e per t of product. Therefore, replacing chemical nitrogen fertilizers with sediments in the JRB could lead to a decrease of nearly 12×10^3 t CO_2e released into the atmosphere. This benefit could be even more significant, as sediments also contain other macronutrients, further reducing the carbon footprint associated with replacing P and K inputs in agriculture as well. Although the sediment reuse technique may involve some CO_2 emissions due to the transport and excavation from reservoir beds, these emissions are expected to be considerably lower compared to those from chemical fertilizers.

3.6 From science to practice

The use of mobile technologies has transformed various 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, insufficient resources to purchase digital devices and poor-quality internet infrastructure. However, advances in communication technologies and the expansion of internet access have allowed these areas to connect locally, regionally and internationally. The democratization of internet and mobile devices access was primarily driven by the significant decrease in the cost of these technologies, improving accessibility. Despite strong social inequalities in Brazil, the country is considered one of the nations that most intensively adopt 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 facilitated the global

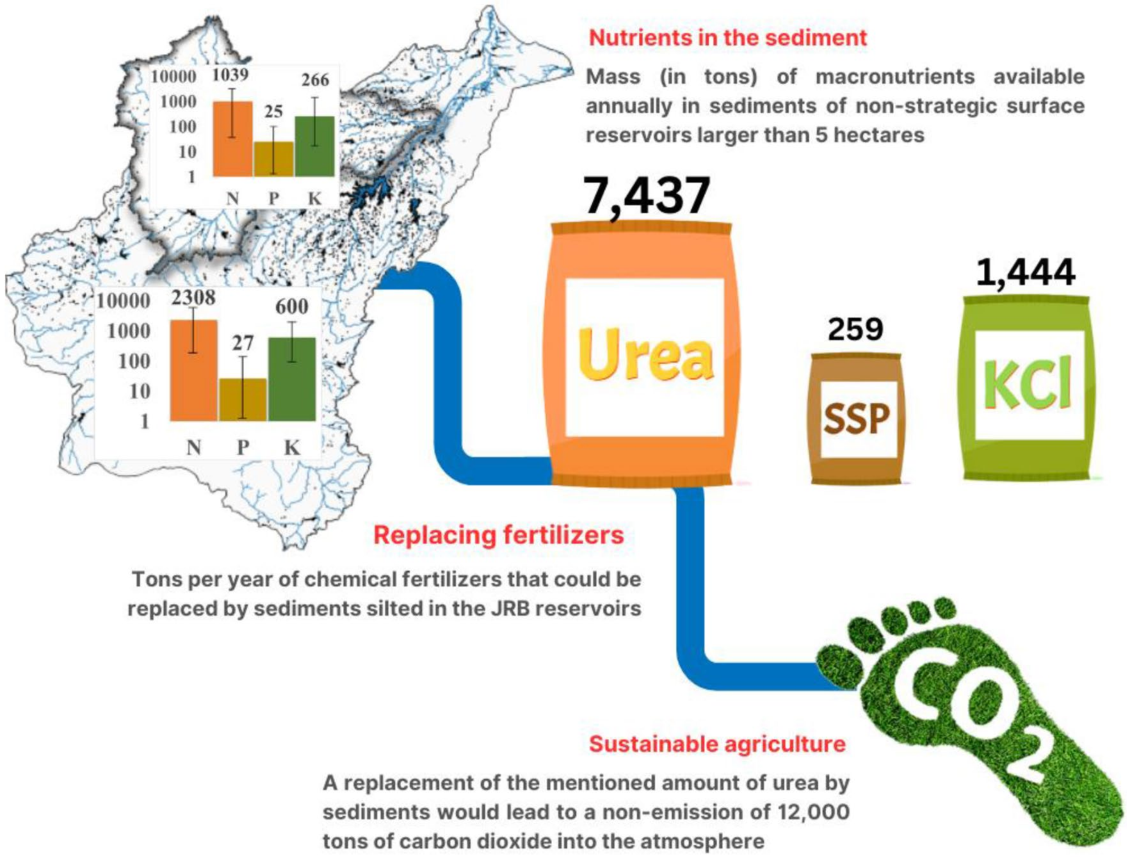

Fig. 9 Annual amount (t year^{-1}) of nutrients (NPK) potentially provided by bottom sediments from non-strategic reservoirs larger than 5 ha in the Banabuiú sub-basin and the Jaguaribe River Basin. The figure also shows the equivalent amount of synthetic fertilizers these nutrients could replace, along with the corresponding reduction in CO_2 emissions from such substitution

dissemination of knowledge and high-quality information among rural producers, institutions, and suppliers (Bambini, Luchiari-júnior and Romani 2014). Mobile information and communication technologies can also enhance productivity among small farmers (Nyamba and Mlozi 2012), providing updates on weather forecast, climate change and the agricultural market, enabling them to make more informed 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, farmers can input their own soil and sediment data to easily calculate the amount of sediment needed to fertilize the soil, meet the demands of the selected crop, and determine whether the practice is financially feasible in their specific situation. The tool is expected to promote the adoption of sediment reuse for agricultural production among small farmers in the study region.

4 Conclusion

This study demonstrates that recycling sediments from reservoir beds in Brazil's semiarid region has the potential to increase crop yields while substantially benefiting the environment and society. However, the spatial and temporal variability of sediment properties pose a challenge to scaling up and widely adopting this practice. As the next step in this research, our goal is to map the nutrient content of soils and sediments on a regional scale using satellite imagery to identify potential reservoirs with sediments suitable for agricultural reuse, as well as nutrient-deficient soils.

The water storage dynamics observed in the study area's reservoirs frequently expose sediments for extended periods, making them easily accessible for excavation and thereby increasing the feasibility of sediment reuse in semiarid regions. The financial feasibility analysis showed that sediment reuse can currently lead to savings of up to 68% compared to conventional fertilization in the region. While chemical fertilizers prices can fluctuate significantly, especially during global crises, sediment reuse costs remain more stable, providing predictability for the agricultural sector. The concentration of zinc and copper in sediments from the study area comply with Brazilian legislation on reservoirs desilting. However, we recognize the study's limitations in terms of inorganic contaminants (only Cu and Zn were evaluated), therefore we recommend that, before considering the reuse of sediments, especially in potentially contaminated areas, complementary analyses be carried out to identify other possible inorganic contaminants, including leaching tests if any element is detected at significant levels. As a perspective to implement the practice in the semiarid area of Brazil, we developed a publicly accessible platform to share our research findings, bringing science and society closer together.

Finally, we propose further research on additional benefits of sediment reuse practice not assessed in this study, such as its potential to enhance soil water retention capacity and its effects on water quality, both by removing nutrient-enriched sediments from reservoirs and by influencing leaching conditions in the soil. Furthermore, to more comprehensively assess the net benefits of reducing the carbon footprint of agricultural production through the adoption of sediment reuse, more detailed studies are needed to quantify the greenhouse gas (GHG) emissions associated with the practice, including those resulting from fossil fuel use during the excavation of dry reservoirs and the transportation of the material to agricultural areas.

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Author contributions BB designed the research study, did the literature review, conducted the data analysis and wrote the first draft; AB and SF designed the research study and methodology, supervised the study and revised the manuscript for publication; GO helped the first author with the literature collection and investigation; PM designed the research study and methodology, supervised the study, raised funds for research and revised the manuscript for publication. All authors read and approved the final manuscript.

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Data availability Data will be made available on request.

Code Availability Not applicable.

Declarations

Ethics approval Not applicable.

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