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SUSTAINABLE RECOVERY PLAN FOR AN URBAN-RURAL COMMUNITY AFFECTED BY THE FUNDÃO DAM DISASTER IN BRAZIL

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Highlights:
- the Fundão Dam toxic tailings damaged the Barra Longa and Gesteira municipalities;
- a massive loss of riparian forest, urban facilities and rural productivity occurred;
- remediation and rehabilitation procedures are feasible Nature-Based Solutions (NBSs);
- a recovery plan based on NBSs with the creation of new greenspaces was proposed.

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Abstract. The rupture of Fundão Dam spilled contaminated tailings across the Doce river basin, severely damaging municipalities such as the urban Barra Longa and the rural Gesteira. The wave of tailings led to the sediment deposition in rivers margins, causing the loss of riparian forests and cropping areas. Sediment analyses confirmed the presence of toxic compounds (sodium and ether amine) and a very low fertility. In consequence, there was a sharp decline in agro-pastoral production in Gesteira, leading to land abandonment and rural exodus. In the urban area of Barra Longa, the wave of tailings damaged the urban floodplain and the square, which were rehabilitated using grey infrastructure. Alternatively, we proposed a new landscape recovery plan for both Barra Longa and Gesteira based on Nature and Community-based solutions that contemplate the inclusion of green infrastructure, the remediation of toxic compounds, the restoration of soil fertility, permeability and stabilization, riparian forest rehabilitation and the recovery of agro-pastoral productivity, ultimately aiming at reducing the flood risk and land abandonment.

Keywords: disaster, ether amine, floodplain, forest restoration, landscape planning, remediation, rural exodus, sodium, social capital.

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1. Introduction

In November 2015, the largest environmental disaster in Brazil occurred as a consequence of the failure of the Fundão Dam in Mariana town, Minas Gerais State. A 30 m wave of mine tailings over the thalweg of Santarem stream reached the Gualaxo do Norte, Carmo and Doce rivers, spreading a total volume of 55 Mm^3 of mine tailing across the basin, vanishing the native riparian vegetation (Santos et al., 2019; Cordeiro et al., 2022), and severely damaging some municipalities such as Bento Rodrigues, Paracatu de Baixo, Gesteira and Barra Longa (Instituto Brasileiro do Meio Ambiente e Recursos Naturais Renováveis [IBAMA], 2015). The riverine population impacted by this disaster was estimated at around 700,000 inhabitants who lost their houses, domestic water supply, agricultural land, irrigation and economic activities (Garcia et al., 2017) including the Krenak and the Pataxó indigenous communities (Lima et al., 2020), settler's communities (Fortes et al., 2022) and the agrarian community of Gesteira that has faced an intense rural exodus due to the lack of water supply, isolation and, especially, the decline in agricultural production (IBAMA, 2015).

The Fundão Dam belonged to the Samarco mine company and was located within the "Quadrilátero Ferrífero" region in Minas Gerais State in Brazil, where large deposits of metamorphosed iron formations are found. The beneficiation of the iron ore is commonly achieved by the reverse cationic flotation technique able to separate the iron minerals from quartz and clays (Araujo et al., 2005; Batisteli, 2007; Peres & Mapa, 2008; Filippov et al., 2014). For that, the reverse cationic flotation process employs starches as oxide depressants and amines (Araujo et al., 2005; Filippov et al., 2014) as cationic collectors of quartz minerals as well as froth stabilizers (Batisteli, 2007). It is estimated that the Samarco company used around 1500 tons/yr of amines in this process (Batisteli, 2007). Ether amine is a primary fatty amine employed in the flotation process at an alkaline pH (>8.5), by the addition of NaOH to stabilize the cationic molecules (Araujo et al., 2005; Filippov et al., 2014). Therefore, the tailings stored in the Fundão Dam and spread in the Doce River basin contained ether amine and sodium (Silva et al., 2015).

Indeed, Santos et al. (2019) detected the presence of ether amine (10–20 mg/kg) and sodium (70 mg/kg) in sediments that reached the Doce River basin after the disaster. High levels of sodium in the soil may inhibit plant growth causing leaf drying and plant mortality by the osmotic stress (Zhu, 2001). Many woody species along Doce river basin showed sodium toxicity symptoms or were found dead after Fundão Dam disaster (Santos et al., 2019). Amines in soil, in turn, may be mineralized or destabilized releasing ammonia/ammonium (NH_3/NH^{4+}), which, at high levels, may be toxic to native and agronomic species, causing leaf chlorosis, leaf curling and, ultimately, plant growth suppression and crop decline (Britto & Kronzucker, 2002; Coskum et al., 2013) and mortality (Britto et al., 2001; Britto & Kronzucker, 2002). On the other hand, tolerant species may present toxicity symptoms such as excessive vegetative growth with stem elongation when exposed to high N-concentrations (Brady & Weil, 2007). In fact, tolerant woody species native to the Atlantic Forest planted in a riparian site in the Gualaxo do Norte River showed excessive vegetative growth reaching 10–20 m, 4 years after transplantation due to the phytoremediation of ether amine (Scotti et al., 2020; Gomes et al., 2021, 2024).

By contrast, metal levels found in riparian areas reached by Fundão Dam tailings did not differ from those of preserved Atlantic Forest (reference site) that were not reached by the tailings (Santos et al., 2019), as also registered by Davila et al. (2020). On the other hand, different authors observed a significative increase in different metals along the Doce river basin (Segura et al., 2016; Paulelli et al., 2022). However, high levels of metals, especially arsenic, were also found in the sediments of the Doce River before the disaster (Santolin et al., 2015; Davila et al., 2020) and some authors used international reference standards to estimate the metals concentration in water and sediments from the "Quadrilatero ferrifero", a region naturally rich in metals. Thus, the increase of some metals such as iron may be attributed to the removal and movement of sediments in the river bottom provoked by the wave of sediment rather than the tailing itself.

Previous research has demonstrated that the remediation of sodium and ether-amine, as well as the recovery of soil fertility is feasible, enabling the establishment of a riparian forest with native Atlantic Forest species (Scotti et al., 2020; Gomes et al., 2021, 2024). However, the Renova Foundation, the sole organisation responsible for proposing, developing and implementing the Doce river basin rehabilitation (Lima et al., 2020) has not adopted any remediation procedures for land rehabilitation, especially in Barra Longa and its rural Gesteira district. The rehabilitation of degraded ecosystems, such as the sites affected by the Fundão tailings, should be achieved using Nature-based solutions (NbS) (Temmerman et al., 2013; Laughlin, 2014; Nel et al., 2014), which has been defined by the International Union for Conservation of Nature as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (International Union for Conservation of Nature, 2020). Thus, the remediation and rehabilitation strategies successfully tested in the affected sites in the Doce River basin (Scotti et al., 2020; Gomes et al., 2021; Fortes et al., 2022; Cordeiro et al., 2022; Gomes et al., 2024) appears as feasible NbSs to integrate urban and rural areas utilising natural and social capitals for the benefit of local communities (Rumbach et al., 2016; Fortes et al., 2022), ultimately reducing the rural exodus in Barra Longa and Gesteira.

Therefore, this study aimed to: (a) assess the toxic compounds and fertility in the sediments of riparian sites of Barra Longa and Gesteira; (b) evaluate the impact of Fundão Dam rupture on the fluvial, riparian and urban areas along the Carmo and Gualaxo rivers in the stretch between Barra Longa town and its rural Gesteira district and (c) propose a recovery plan of the blue-green infrastructure, including the rehabilitation of riparian forests and the recovery of cropping areas as well as the urban environment.

2. Materials and methods

2.1. Study site

The study area is located in the Doce river basin (Mariana, Minas Gerais State, Brazil) which was affected by the tailings from the Fundão Dam, comprising the stretch from Gesteira to Barra Longa municipalities along the Carmo and Gualaxo rivers as shown in Figure 1. This area is inserted within the geomorphological unit known as "Quadrilátero Ferrífero". The climate is classified as subtropical highland (CWb), with hot and rainy summers, dry winters, and an average annual rainfall of 1,552 mm (Oliveira & Salgado, 1987).

The Barra Longa municipality is located along the Carmo river, a tributary of the Doce river, and extends over 386 km^2, including both urban and rural areas. The estimated population in 2010 was 2,313 inhabitants in urban areas and 3,830 inhabitants in the rural area distributed across several small districts. One of the districts most affected by the dam tailings was Gesteira (Figure 1), a rural community located ~10 km from the Gualaxo do Norte River. The main source of income in Barra Longa was the agro-pastoral activities (e.g., dairy cattle and crops) produced in Gesteira.

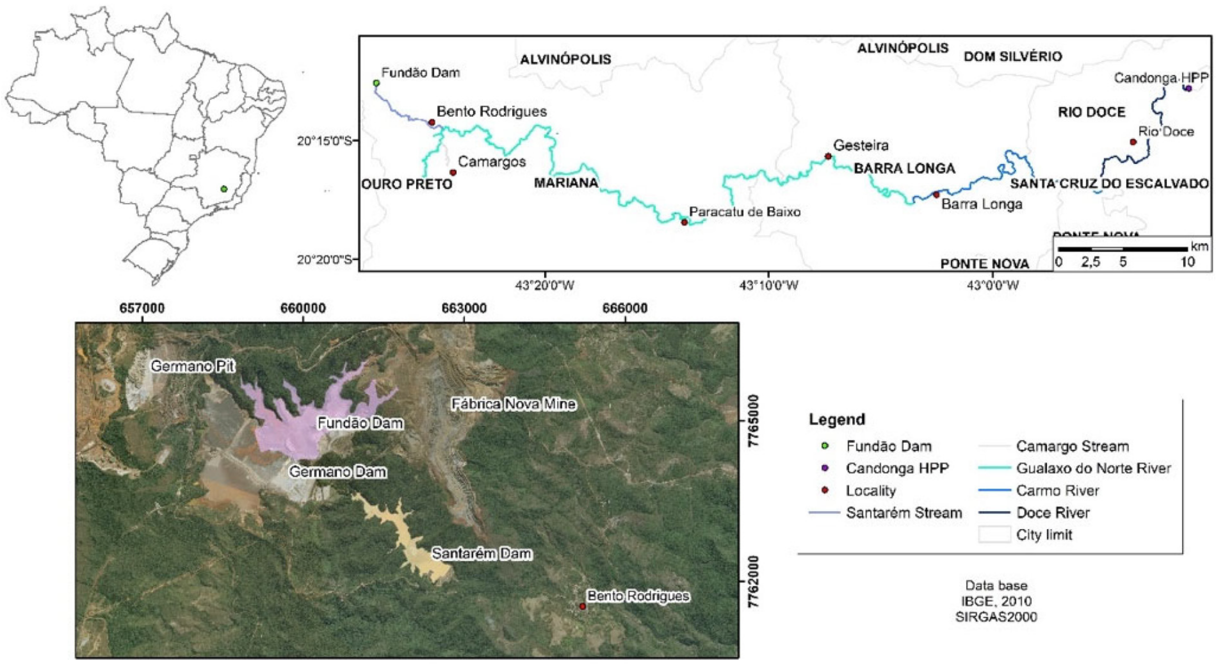


Figure 1. Area reached by the Fundão Dam tailings in Minas Gerais State (Brazil), highlighting Gualaxo do Norte, Carmo and Doce rivers and the affected municipalities (Barra Longa and Gesteira) (source: IBGE, 2010; Google, 2022)

2.2. Hydrological studies

The ArcGIS software (version 10.5) was used to delimit the areas affected by the mine tailing based on interpretation protocols and considering variables such as the colour, shape, location and texture of the elements examined, as well as geo-referencing the satellite images. The Geocentric Reference System for the Americas (SIRGAS) and Albers Equivalent Conic Projection were used to calculate the areas. The study area was evaluated using Landsat/Copernicus satellite images obtained using Google Earth Pro software (version 7.3.3) prior to and after the disaster. These data consisted of a mosaic of 411 images with a spatial resolution of 8 m, obtained before the disaster, and 263 images with a spatial resolution of 3 m, obtained after the dam collapse. Tailing thickness was estimated based on Jacobs (2018) along transects transverse to the watercourses, in areas close to the banks (alluvial plains and hillsides as well as instream) using a modified penetration test (Nixon, 2021) through manual probing coupled with excavators and augers.

2.3. Environmental impact assessment

Chemical analyses of nutrients, exchangeable cations and metals found in the sediments collected in 2017 were performed according to the Brazilian Agricultural Research Corporation (1997). Total inorganic N was determined by semimicro-Kjeldahl digestion (Bremner, 1960), and NH_3 and NO^{3-} content were determined according to Bremner and Keeney (1965). The quantification of ether amines in soil and sediment samples was performed using the colorimetric bromocresol green methodology described by Araújo et al. (2009) and the detection was performed using a spectrophotometer (Shimadzu UV-160A), using as ether amine standards the Flotigam EDA 3 and Fotigam 2835-2. The soil microbial biomass was estimated by Phospholipid fatty acids (PLFAs) analysis which were extracted from lyophilized soil according to the Bligh and Dyer method (Bligh & Dyer, 1959), and the lipid fractionation was performed according to Gehron and White (1983) and White et al. (1979).

2.4. Agro-pastoral productivity

The estimation of agro-pastoral productivity in the rural area (Gesteira) before and after the disaster was based on data from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística [IBGE], 2017). After the environmental, economic and social assessments as well as a face-to-face and informal consultative meeting with the rural community, we proposed a land rehabilitation plan for Gesteira.

2.5. Landscape evolution and recovery plan

To assess the evolution of the landscape of the stretch from Barra Longa to Gesteira, images obtained from Google Earth, AutoCAD (version 2018), photoshop CS6 and SketchUp (version 2018) software were used, as well as photographic records. A new rehabilitation proposal for the town and its rural areas was developed using the software mentioned above, as well as a schematic design and simulations. Such a plan was based on the recovery of ecosystem functions with direct benefit to the population (NbS) using a sustainable technology previously reported by Scotti et al. (2020) and Gomes et al. (2021, 2024).

2.6. Statistical analysis

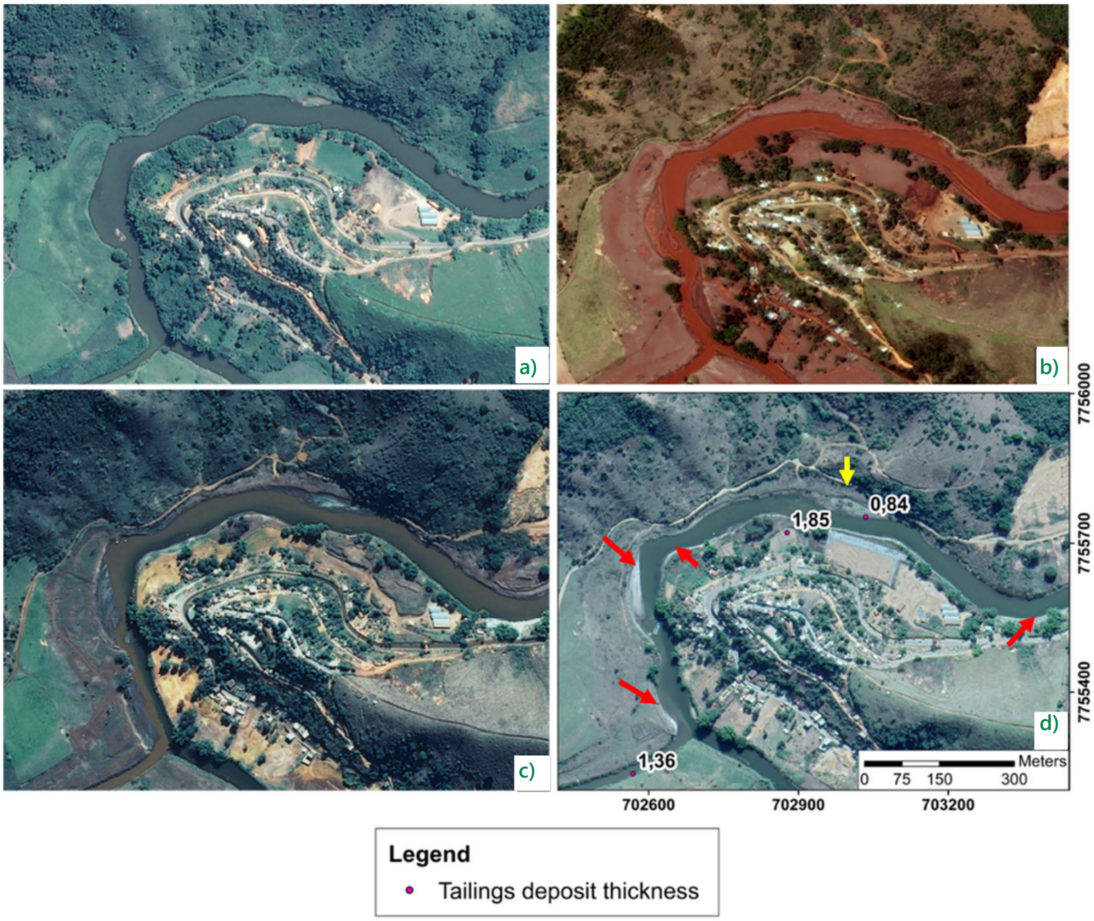
The studied variables were compared among the preserved, Barra Longa and Gesteira sites. Analysis of variance (one-way ANOVA) was used for the variables with normal distributions. Multiple comparisons were performed with a Tukey test using SPSS v. 20 software. The significance level was set at $p \leq 0.05$ for all analyses.

3. Results and discussions

3.1. Hydrological studies

Figure 2 shows the impact of the dam tailings over the Barra Longa floodplains by comparing the landscape before (Figure 2a) and after the disaster (Figures 2b–2d). The sediments were deposited 100 m from the Carmo River margin (Figure 2b), covering a total area of 0.24 km^2 along the right bank and 0.31 km^2 on the left bank, covering approximately 32.4% of the urban area of Barra Longa (Figure 2b). The sediment thickness deposited in the floodplains in 2018 varied from 0.84 m to 1.85 m in the Carmo River, while in the Gualaxo do Norte River, the sediment thickness was 1.36 m (Figure 2d). Such sediment deposition in the margins changed the fluvial depositional dynamics, resulting in the formation of several sand bars (red arrows) as well as an increase in the size and extension of the original sand bars (yellow arrow) as shown in Figure 2d. Similar results were observed by Oliveira et al. (2017) and also by Cordeiro et al. (2022) who reported a sediment deposition thickness as high as 5.76 m in other regions affected by the dam tailings. The wave of tailings affected floodplains in both rural and urban zones in Barra Longa, destroying riparian forests, cropping areas, roads, houses and squares (IBGE, 2017).

In the rural area of Gesteira, agricultural properties were located along the riparian zone of the Gualaxo do Norte River as observed in Figure 3a, before the disaster. After the dam rupture, around 20,480 m^3 of sediment were deposited in this stretch of the Gualaxo do Norte River (Figure 3b). Similar to Carmo River, the sediment deposition in the margins of this river modified the fluvial dynamics with the formation and dislocation of sand bars (Figure 3d). However, the main impact in Gesteira was the massive loss of rural properties in this floodplain (Figures 3b–3d) as well as houses, schools and the Our Lady of Conception church built in 1891 (Jacobs, 2018).



Note: Red arrows: newly formed sand bars. Yellow arrow: increased sand bar.

Figure 2. Urban area and floodplain of Barra Longa before (a) 2013 and after the Fundão Dam disaster (b) 2015, (c) 2016 and (d) 2018 (source: Google, 2022)

Figure 3. District of Gesteira before the disaster (a) in July 2015 and after disaster (b) in November 2015; (c) August 2016 and (d) July 2020

3.2. Impact of dam tailings over riparian areas of Barra Longa and Gesteira

As registered along the Gualaxo do Norte River (Santos et al., 2019; Cordeiro et al., 2022), especially in Paracatu de Baixo (Scotti et al., 2020; Gomes et al., 2021), the main impact of dam tailing was the decline of plant growth and survival due to the sediment toxicity, the high sediment pH and the loss of soil fertility with the reduction of macronutrients as K, Ca and Mg but not P (Table 1). Such results may be understood since the natural rocks in the "Quadrilátero Ferrífero" region are rich in phosphorus (Spier et al., 2007; Baião et al., 2021). The mineral elements as Cu, Zn, B, Fe and Mn did not differ from preserved site (Table 1). These results demonstrate that these elements are not toxic to plants native to this region, confirming previous results reported along the Doce River basin (Santos et al., 2019; Scotti et al., 2020; Fortes et al., 2022).

The high sediment pH can be explained by the presence of sodium and ether amine, which are the main toxic compounds found in riparian sites of Barra Longa and Gesterira (Figures 4a and 4b) which were significantly higher than the Preserved site (Atlantic Forest). It was found similar ether amine contents in samples from Barra Longa and Gesteira but in the former the sodium content was higher than the latter. Sodium toxicity may compromise plant water uptake and photosynthesis (Zhu, 2001) as well as provoke the increase of soil pH and ecotoxicity events as reported in bauxite mine disaster in Hungary (Klebercz et al., 2012). Indeed, the increase in sediment pH observed in Barra Longa and Gesteira (Table 1) was attributed to the high sodium content in the sediments which may affect the soil properties (Quirk, 2001) such as cationic exchange capacity (CEC) and electrical conductivity (Gomes et al., 2021), soil permeability and aggregation resulting in plant growth inhibition (Abbas et al., 2016). However, the remediation of sodium (from 50 ppm to 20 ppm) in a riparian forest reached by Fundão tailings was achieved by the incorporation of organic matter able to improve the adsorption of ionic compounds, allowing the plant survival and growth (Scotti et al., 2020; Gomes et al., 2021, 2024).

Table 1. Chemical and physical analyses of sediments collected in 2017 at different riparian impacted riparian sites in Barra Longa and Gesteira and Preserved Site (Lavras Velhas River)

Variables	Sites	Mean	SD	P value	Multiple comparison preserved site
pH	Preserved	5.47	1.0	0.004	
	Barra Longa	8.3	0.61		0.016
	Gesteira	8.34	0.59		0.013
Phosphorus – P (ppm)	Preserved	8.79	2.54		
	Barra Longa	5.83	2.79	0.105	0.677
	Gesteira	5.17	2.14		0.358
Potassium – K (ppm)	Preserved	65.0	10.06		
	Barra Longa	20.17	19.2	0.001	0.048
	Gesteira	14.5	1.05		0.005
Calcium – Ca (ppm)	Preserved	465.17	109.15		
	Barra Longa	175.67	86.5	0.001	0.043
	Gesteira	172.8	72.0		0.027
Magnesium – Mg (ppm)	Preserved	114.83	46.6		
	Barra Longa	22.33	9.9	0.001	0.032
	Gesteira	20.8	9.0		0.022
Sulfur – S (ppm)	Preserved	8.67	3.4		
	Barra Longa	16.5	6.5	0.005	0.005
	Gesteira	18.33	8.3		0.004
Boron – B (ppm)	Preserved	0.19	0.07		
	Barra Longa	0.12	0.04	0.07	0.3
	Gesteira	0.2	0.09		1.0
Copper – Cu (ppm)	Preserved	2.07	1.4		
	Barra Longa	0.7	0.5	0.02	0.235
	Gesteira	0.65	0.11		0.71
Iron – Fe (ppm)	Preserved	254.33	67.7		
	Barra Longa	220.50	155.70	0.055	0.523
	Gesteira	187.50	6.47		0.938
Manganese – Mn (ppm)	Preserved	234.33	208.5		
	Barra Longa	302.33	66.5	0.144	1.0
	Gesteira	403.8	107.9		0.8
Zinc – Zn (ppm)	Preserved	4.7	0,36		
	Barra Longa	0.52	0,33	0.002	0.078
	Gesteira	0.55	0.11		0.268

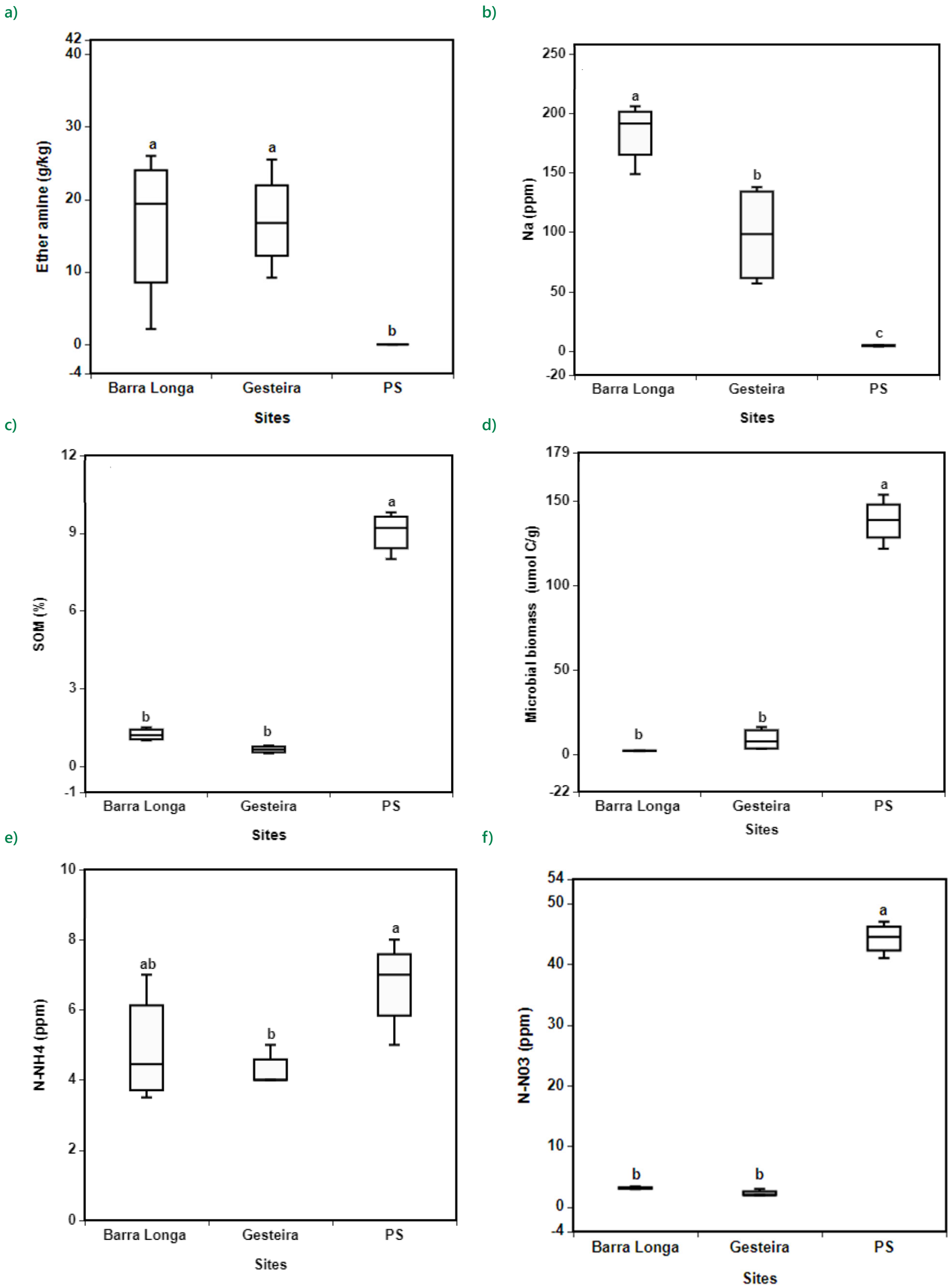
Note: Analysis of variance ANOVA was applied and means were compared by Tuckey's test (Different lowercase letters per column indicate differences at ($p \leq 5\%$).

The Cationic Exchange Capacity (CEC) was strongly reduced in Gesteira and Barra Longa. The CEC reduction may be attributed to the lack of organic matter in the sediments (Figure 4c) which also presented a very low clay content (Santos et al., 2019), characterizing a very low fertility. Besides, the alkaline stress may affect the soil microbial communities (Frostegård & Bååth, 1996), which were found severely inhibited in both Barra Longa and Gesteira soils in comparison to those from the preserved site (Figure 4d). Such strong impact over soil microbial community in the Fundão Dam sediments was also described by Santos et al. (2019) and explains the depletion in N fertility in this area. While there was a decrease in $N\text{-}NO_3$ in the sediments, the $N\text{-}NH_4$ content remained high in both Barra Longa and Gesteria (Figures 4e and 4f). This result may be explained by the decomposition of ether amine releasing ammonium/ammonia ions (Gomes et al., 2021). Under normal soil fertility conditions, the ammonium should be oxidized to nitrate by soil bacteria through the nitrification process (Zhu & Wen, 1992; Santamaria et al., 1998) and consequently most crop species prefer $N\text{-}NO_3$ nutrition (Heberer & Below, 1989). However, the nitrate content in Barra Longa and Gesteira soils was found very low (Figure 4f) which may be attributed to the strong inhibition of microbial populations and the nitrification process. Therefore, the low fertility caused by the reduction of nutrients, the low CEC and, especially, the very low nitrate availability compromised the agricultural productivity in Gesteira as also observed in rural settlement properties of the Ipaba district in the Doce River basin after the disaster (Fortes et al., 2022). Thus, the recovery of soil fertility will depend on the remediation of toxic compounds (sodium and ether amine) as demonstrated by Scotti et al. (2020) and Gomes et al. (2021, 2024).

3.3. Impact of dam tailings on Barra Longa urban area

The riparian area of Barra Longa town was entirely covered by dam tailings from the Gualaxo do Norte River, which severely affected its main street (Beira Rio Street) and the main square (Manoel Lino Mol Square) (Figures 5a–5e). The Manoel Lino Mol Square was built in 1971 and constituted the major greenspace of the town with a high density of trees which provided shade and thermal comfort to this warm municipality whose annual mean temperature reaches 26 ºC. It was the main leisure area of the town for social, sports and recreational activities (Figures 5a and 5c). However, the wave of dam tailings turned it into a devastating scenario of mud and stones (Figures 5b, 5d and 5e), with only a very few woody species remaining (Figure 5e).

The Renova Foundation has re-constructed the Manoel Lino Mol Square (Samarco, 2017). This project retained a rectilinear design, and communal gardens were constructed with grasses and some shrubs (Figures 6a and 6b). However, the greenspace was greatly reduced to small gardens surrounded by a large area of grey infrastructure as the impermeable paving (Figure 6b). Metal chairs, lighting and gym facilities were installed, and a huge wooden deck was built, stretching from the square to the floodplain (Figures 6c–6e). The aspect of the new square most criticised by the local population was the marked reduction in greenspace, particularly the lack of trees, and its replacement with a large grey space, largely compromising



Note: The analysis of variance was performed using ANOVA or a Kruskal–Wallis test, and for pairwise comparisons Tukey's or Nemenyi's tests were used. Means followed by the same letters did not show significant differences (at $p \leq 0.05$).

Figure 4. Comparisons of contents of etheramine (a) sodium (b), soil organic matter (c) content, microbiol biomass (d), NH_4 (e) and NO_3 content (f) among the preserved site (PS), and impacted sites of Gesteira and Barra Longa

the important eecosystem functions provided by urban greenspace to local residents such as climate and radiation regulation, thermal comfort, air and water purification and pollution control (Tzoulas et al., 2007; Liu et al., 2018).

In addition, the riparian site was unadvisedly covered with wooden decking and stone paving, making the urban riparian area impermeable (Figure 6e). Also, the floodplain along the Carmo River in Barra Longa has been paved with stone (Figure 6f), covered with plant-derived fibre mats (Figure 6g) or even replaced with forest soils brought in from elsewhere (Silva et al., 2015). From the perspective of environmental best practice, such measures employed for flood risk management in Barra Longa are environmentally damaging since they increase the impervious surface, compromising the water dynamics and increasing the impermeability due to the increase of grey infrastructure in detriment of greenspaces (Hamlin & Nielsen-Pincus, 2020; Woodruff et al., 2020). In addition, the fibre blankets and mats used in the riparian rehabilitation procedures (Figure 6g) decomposed rapidly, not allowing the margin area to stabilise (Cordeiro et al., 2022). Such accelerated decomposition rates were attributed to the presence of N-compounds, such as ammonia (NH_3) or N-ammonium, derived from the biodegradation of ether-amines found at high concentration in the dam tailings (Santos et al., 2019), particularly in Gesteira and Barra Longa (Figure 4e).

By contrast, riparian forest rehabilitation offers a reliable nature-based solution (NbS) for flood and erosion control, since it provides ecosystem functions (Meraj, 2020) that assures floodplain drainage as well as soil aggregation and porosity, particularly in areas under anthropic and urban pressure, including agriculture, pasture and industrial activities (Lowrance et al., 1997; Sheridan et al., 1999; Schultz et al., 2004). Accordingly, in Brazil, Kimura et al. (2017) created a successful rehabilitation model under a buffer zone system, to rehabilitate a degraded riparian forest under periodic flooding using native species, which may be replicated in Barra Longa. This NbS has been successfully tested in other areas affected by dam tailings such as in Paracatu de Baixo (Scotti et al., 2020; Gomes et al., 2021, 2024) and these actions may be also replicated in Barra Longa after remediating the sediment toxicity. The success of phytoremediation and bioremediation with plant growth-promoting bacteria assured the recovery of different ecosystem functions such as the establishment of native species, improvement of soil fertility, increase in soil microbial populations, soil aggregation and stabilization (Gomes et al., 2024). The stabilization of such disaggregated sediment may prevent the translocation of contaminated tailings deposited in riparian areas to Doce River watershed.

3.4. Landscape recovery plan for the urban Barra Longa

Considering the wishes of the local community and environmental issues regarding the rehabilitation of the Lino Mol Square and floodplain by the Renova Foundation (Figures 6a, 6b), we present a new rehabilitation proposal. First, we propose to remove the grey infrastructure such as the wooden deck (Figures 6d, 6e) and the stone paving (Figures 6f), which should be replaced with greenspaces composed of riparian forests planted with Brazilian Atlantic Forest species as successfully demonstrated by Gomes et al. (2021, 2024). Such riparian forest should be created to form buffer zone systems to improve sedi-

Figure 5. Overview of square Lino Mol before (a and c) and after the Fundão Dam disaster (b, d and e) in Barra Longa municipality

Figure 6. Rehabilitation of the Lino Mol Square (a and b); coverage of the riparian area with a wood deck (c, d and e), stones (e and f) and plant-derived fibre mats (g)

ment stabilisation, drainage and, ultimately, flood control, as proposed by Kimura et al. (2017). The urban greenspace should also be changed by planting woody species in the Lino Mol Square communal gardens (Figure 6b) in addition to grasses with its branching roots since a balanced combination of trees, shrub and herbaceous species may provide the maximum ecosystem functions (Meraj, 2020) to urban greenspaces (Liu et al., 2018). Prior to both interventions, it is strongly recommended that the remediation strategies described in Scotti et al. (2020) and Gomes et al. (2021, 2024) should be adopted, to reduce ether-amine and sodium toxicity and guarantee tree cultivation success.

The main deleterious consequence of paving the floodplain with grey infrastructure as stones is the increased flood risk (Hamlin & Nielsen-Pincus, 2020; Woodruff et al., 2020), resulting in serious ecological and socio-economic problems (Gurusamy & Vasudeo, 2023). Thus, we highly recommend the removal of the paving and mats along the floodplains of the Carmo river (Figure 6g), followed by the planting of riparian forests with woody species using the buffer zones systems (Kimura et al., 2017). Although the removal of tailings performed by Renova Foundation in the riparian sites of Barra Longa may be a recommended remediation procedure in some cases, its replacement with forest soils may imply the degradation of the sites where the soil is sourced from, as documented by Silva et al. (2015), thus, constituting a new environmental impact. Additionally, this information becomes relevant for those researchers who have inadvertently collected soil samples in the Carmo river floodplain in Barra Longa after 2017, since they have sampled and reported data not from the sediments of the Fundão Dam.

3.5. Impact of dam tailings on the rural area of Gesteira

The Figure 7a shows the changes in the rural area of Gesteira caused by the wave of dam tailings as compared to the conditions before the disaster. The rural riverine populations were settled along the Gualaxo do Norte River and their main economic activities relied on agriculture and grazing (Senna, 2019). This community faced the entire destruction of their houses and subsistence agricultural activity, leisure and communal spaces (e.g., schools, bars, football pitches), roads, as well as the damage to religious and cultural facilities (Figure 7 a2, a3 and a4). The loss of houses and productive land resulted in the rural exodus or displacement of families to areas not affected by the dam tailings (Figure 7b). Accordingly, Silva (2018) and Senna (2019) reported that such land abandonment resulted in the separation and dispersal of families, aside from the development of allergic and mental health problems (e.g., post-traumatic stress disorder and major depression).

After the disaster, there was a marked loss of greenspaces, including both preserved forest and crop areas, which were covered by the dam tailings. While the crop areas became unproductive, there was no natural regeneration of riparian Atlantic Forest, which reduced from 61% to 6% (Cordeiro et al., 2022). Such a low level of resilience may be attributed to the ether-amine and sodium toxicity found in the sediments (Figures 4a and 4b) which also led to the mortality of adult trees in the field (Santos et al., 2019) as well as the decline in crop productivity due the very low fertility levels, especially nitrate (Figure 4f), as also confirmed by Fortes et al. (2022).

Data from Table 2 shows the decline of agro-pastoral productivity in Gesteira after the Fundão Dam disaster. The crops that most declined in Gesteira from 2015 to 2017 were: corn (80%), bean (78%) and sugarcane (53%), while sheep, goat and swine herds declined 93%, 85% and 57%, respectively. Senna (2019) also reported that horticulture and fruits production never recovered in Gesteira after the disaster. The decline in crop productivity may be caused by the toxic effect of the sediments on vegetation, likely due to the overload of NH_4^+ derived from ether-amines and/or Na as well as nitrate and SOM depletion. In fact, Fortes et al. (2022) demonstrated that the crop decline in settlers' properties in Ipaba, a riverine municipality of the Doce river, was associated with high sodium content and low nitrate availability for plants. Accordingly, Andrade et al. (2018) observed a reduction in grain yields and the root growth of rice cultivated in a mixture of contaminated tailings and soil under greenhouse conditions.

3.6. Landscape recovery plan for Gesteira

The pivotal social consequence of the Fundão Dam disaster was the rural exodus. The reversal of this process may be achieved only through the recovery of the crop productivity of the affected areas as proposed in Figure 8. The main rehabilitation steps are presented in Figure 8, as follows:

Environmental and Economic recovery: Soil remediation (Step 1) should be adopted by employing phytoremediaiton and physico-chemical remediation procedures described by Scotti et al. (2020) and Gomes et al. (2021, 2024) that will ensure the recovery the soil fertility and agricultural production (Step 4), as well as the establishment of a riparian forest in the Gualaxo river floodplains (Step 8) using a buffer zone system (Kimura et al., 2017) with Atlantic Forest species Gomes et al. (2021, 2024). These actions could not only remediate the sodium and ether-amine contents but also help the retention of sediments in the margins, preventing these chemical pollutants from reaching the agricultural sites (green barrier), ultimately improving the water quality. The rehabilitation may be an essential strategy for the protection not only of the agricultural properties, enabling the recovery of agro-pastoral activities, but also protecting the farms from floods (Hamlin & Nielsen-Pincus, 2020), being a balanced socio-economic and ecological solution to prevent hazards from flooding (Gurusamy & Vasudeo, 2023).

Community-based solutions are effective strategies to enable rural communities to recover after disasters (Pyles, 2007; Regnier et al., 2008; Song et al., 2017;

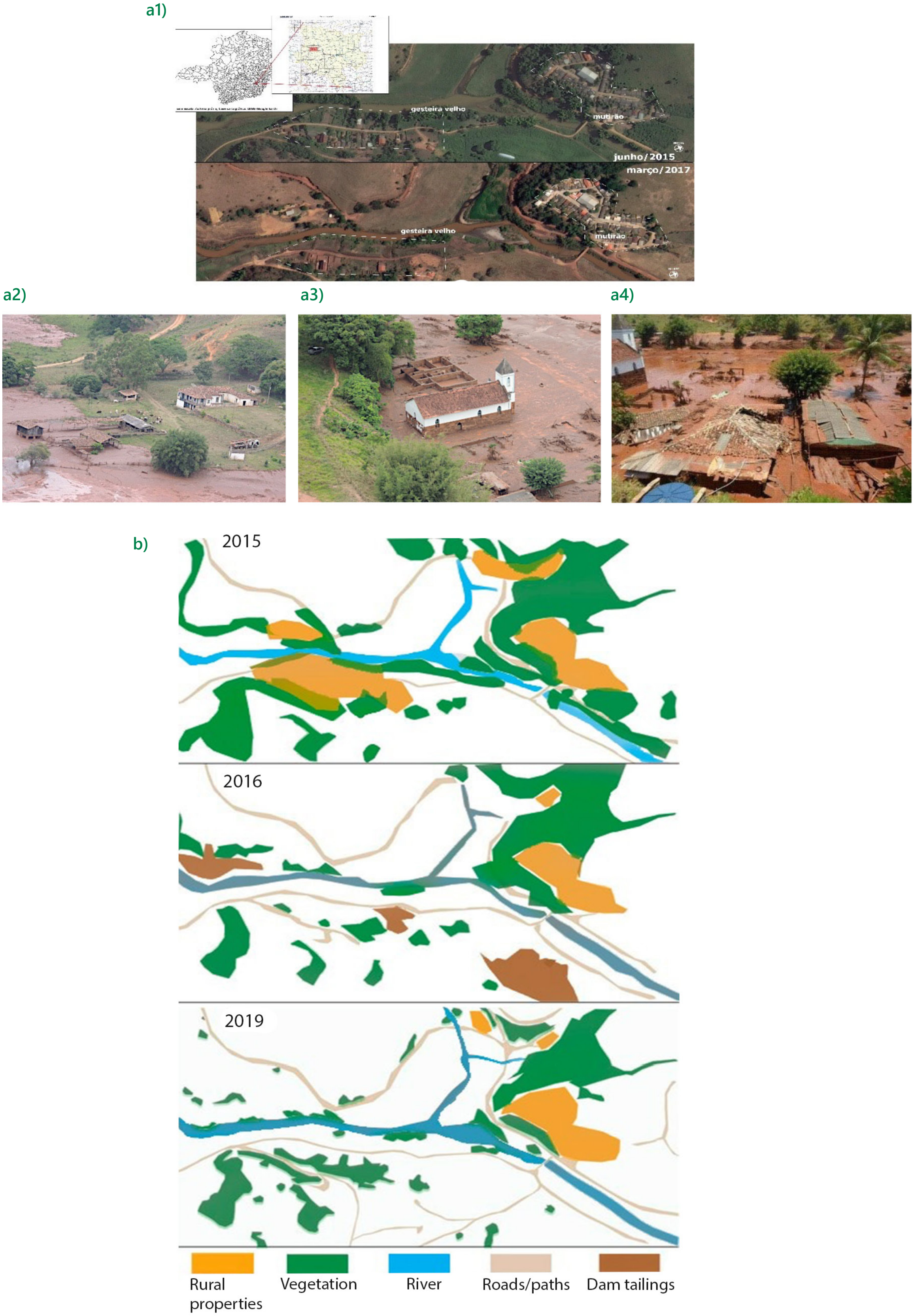


Figure 7. a) Riparian rural areas of Gesteira before (a1-2015) and after the impact (a1-2017 and a2) of dam tailing, the Our Lady of Conception church (a3) and houses as well as the open market (A4); b) Landscape changes in riparian areas of Gesteira highlighting the green spaces and rural properties before (2015) and after the disaster (2016 and 2019)

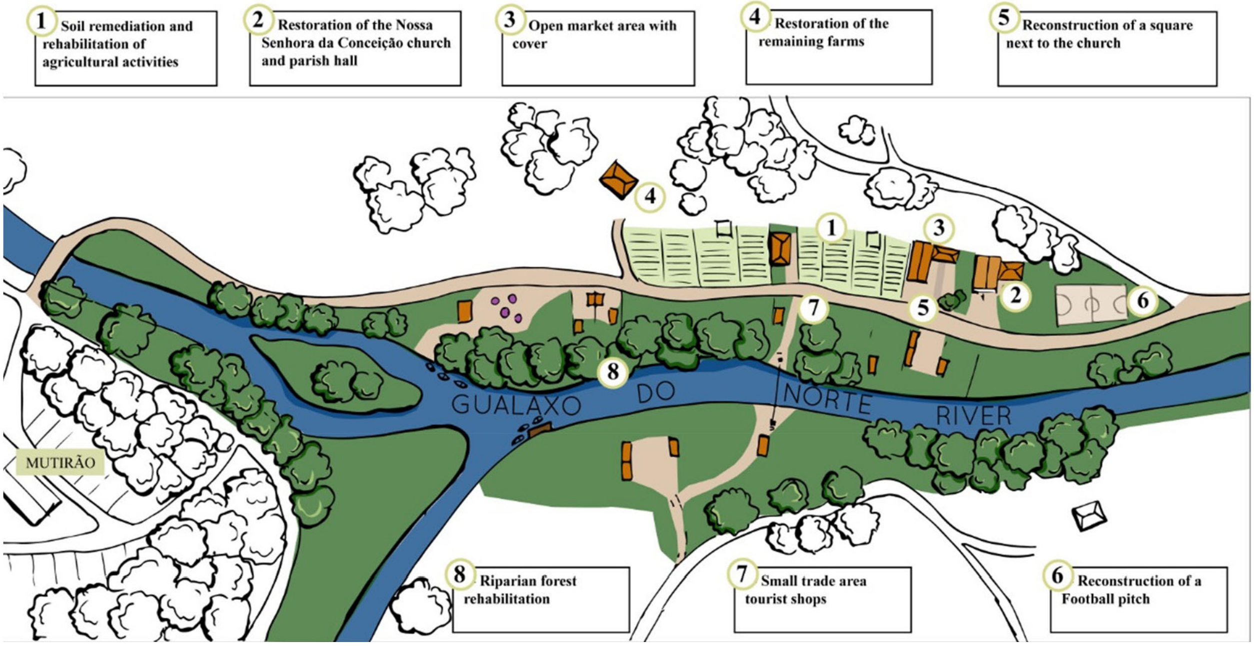


Figure 8. Recovery plan with the main restoration procedures (steps 1–8) for the rural properties of Gesteira based on Nature and Community-based solutions

Whittaker et al., 2013) and stabilise them in the field. Disaster recovery has been based not only on the repair and reconstruction of facilities and activities to return the pre-disaster conditions (Johnson & Hayashi, 2012), but also on the improvement of community resilience and well-being (Rouhanizadeh et al., 2020; Jones et al., 2022), which should be guided by the *building back better* concept to mitigate the underlying risks (Fernandez & Ahmed, 2019; Jones et al., 2022). Thus, we proposed a sustainable rehabilitation plan for Gesteira contemplating the creation of market and shopping areas to make possible the sale of agricultural products, general goods, arts and crafts and fresh foods (Figure 8, Steps 3 and 7). On the other hand, the protection and recovery of cultural and religious heritage such as the church and cemetery as well as the creation of a square to promote religious and cultural events will be essential actions aimed at reducing the rural exodus after the disaster, as proposed in Steps 2 and 5 (Figure 8). The improvement of tourism and leisure activities constitutes another relevant social aspect, particularly for young people. Thus, we proposed the creation of spaces for festivities and sports (e.g., football pitches) as presented in Figure 8 (Steps 5 and 6). Fortunately, the school "Gustavo Capanema" was rebuilt in the "Mutirão" region (Figure 8) by the Renova Foundation.

This recovery plan needs to contemplate approaches proposed by Nature and Community-based solutions (Russo et al., 2017; Lilli et al., 2020) to guarantee the success of urban and rural rehabilitation, ultimately halting the rural exodus. It is worth mentioning that communities like those from Gesteira generally have a low capacity to self-organise after disasters (Imperiale & Vanclay, 2016), therefore the lack of resources and aid dependency are major obstacles for disaster mitigation (Trogrlić et al., 2017). Social capital theory explains how individuals and social groups may have access to land, labour and other forms of physical capital through social networks and associations based on the establishment of mutual trust values (Rumbach et al., 2016; Roque et al., 2020; Straub et al., 2020). Therefore, social capital arises as the most feasible solution to the social, environmental and economic recovery of Gesteira. Once farmers can restore agro-pastoral production on their lands, particularly of corn, sugarcane, bean and grazing activities (Table 2), it will be possible to market their rural products (Cechin et al., 2021) and improve tourism in the region as shown in Figure 8. To achieve this, social capital theory suggests the creation of associations that encompass not only farmer representatives from Gesteira but also other social actors such as local citizens, community stakeholders, governmental entities, policy-makers, urban planners, the prosecutor's office and private companies to stitch together solutions and to collectively provide financial support to recover from the disaster (Ritchie & Gill, 2007; Aldrich & Meyer, 2015). Also, a technology diffusion program aiming at training the farmers to apply the proposed NBSs in their lands is needed, which may be achieved by providing technical support to the rural association representatives by governmental entities. Once the farmers are able to properly manage their lands and recover the agro-pastoral productivity, it may become a sustainable source of income for this community as previously reported by Cechin et al. (2021) in a Brazilian rural settlement.

Table 2. Agropastoral production/Year in Gesteira (MG) before (2006–2015) and after Fundão Dam disaster (2017) (source: IBGE – Agriculture and livestock production, 2014, 2015)

Agropastoral production/Year	2006	2015	2017
Crop (TonYear^{-1})			
Sugarcane	3200	12 600	5980
Bean	1700	2070	450
Corn	3600	2400	480
Livestock (individuals year^{-1})			
Cattle	20 880	–	14 482
Goats	223	–	34
Equine	842	–	583
Swine	1049	–	455
Sheep	147	–	10

4. Conclusions

This study assessed the impact of the Fundão Dam disaster on the hydrology, landscape, riparian soils, urban structure and agro-pastoral productivity in Barra Longa and Gesteira municipalities. The main environmental impacts were the sediment deposition in the floodplain of Carmo and Gualaxo do Norte rivers, the phyto-toxicity caused by ether amine and sodium and the very low fertility of sediments, resulting in the loss of riparian forests and cropping areas. Since the urban area of Barra Longa was rehabilitated with grey infrastructure, we proposed an alternative landscape recovery plan including new greenspaces in both the urban and rural areas as well as the establishment of riparian forests with native species, which will contribute for leisure space, climate and thermal comfort, air and water purification, besides reducing the flood risk. This new proposal based on Nature and Community solutions will hopefully allow the increase of agro-pastoral productivity and reduce the rural exodus.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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