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Essays and Perspectives

Deep into the mud: ecological and socio-economic impacts of the dam breach in Mariana, Brazil

Geraldo Wilson Fernandes[a,b,*], *Fernando F. Goulart*[c], *Bernardo D. Ranieri*[d], *Marcel S. Coelho*[a,e], *Kirsten Dales*[f], *Nina Boesche*[g], *Mercedes Bustamante*[h], *Felipe A. Carvalho*[a], *Daniel C. Carvalho*[i], *Rodolfo Dirzo*[b], *Stephannie Fernandes*[j], *Pedro M. Galetti Jr.*[b,k], *Virginia E. Garcia Millan*[g], *Christian Mielke*[g], *Jorge L. Ramirez*[k], *Ana Neves*[a], *Christian Rogass*[g], *Sérvio P. Ribeiro*[l], *Aldicir Scariot*[m], *Britaldo Soares-Filho*[c]

[a] *Evolutionary Ecology & Biodiversity, Department of General Biology, Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, MG, Brazil*
[b] *Department of Biology, Stanford University, Stanford, United States*
[c] *Master in Modeling and Analysis of Environmental Systems, Center for Remote Sensing, Department of Cartography, Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, MG, Brazil*
[d] *Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, Canada*
[e] *Laboratory of Phenology, Department of Botany, Instituto de Biociências (IB), Universidade Estadual Paulista (UNESP), Rio Claro, SP, Brazil*
[f] *Canadian International Resources & Development Institute, University of British Columbia, Vancouver, Canada*
[g] *Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Geodesy and Remote Sensing Department, Potsdam, Germany*
[h] *Department of Ecology, Universidade de Brasília, Brasília, DF, Brazil*
[i] *Department of Zoology, Pontifícia Universidade Católica de Minas Gerais (PUC-Minas), Belo Horizonte, MG, Brazil*
[j] *Faculdade de Direito Milton Campos, Nova Lima, MG, Brazil*
[k] *Department of Genetics and Evolution, Universidade Federal de São Carlos, São Carlos, SP, Brazil*
[l] *Department of Biodiversity, Evolution and Environment, Institute of Exact and Biological Sciences, Universidade Federal de Ouro Preto, Ouro Preto, MG, Brazil*
[m] *Embrapa Recursos Genéticos e Biotecnologia, Parque Estação Biológica (PqEB), Brasília, DF, Brazil*

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ABSTRACT

We review the ecological and socio-economic impacts of the catastrophic dam failure in Mariana, Brazil. Tailing management practices by Samarco mining company ultimately caused a dam breach that abruptly discharged between 55 and 62 million m^3 of tailings into the Doce River watershed. On November 5th, 2015, a tsunami of slurry engulfed the small district of Bento Rodrigues, loading the Doce River and its estuary with toxic tailings along a 663.2 km trajectory, extending impacts to the Atlantic coast. Acute ecological impacts will adversely affect livelihoods of more than 1 million people in 41 riparian municipalities by reducing local access to fisheries resources, clean water, crop production sites, hydroelectric power generation and raw materials. The threats to riverine human communities are

* *Corresponding author.*
E-mail address: gw.fernandes@gmail.com (G.W. Fernandes).
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particularly critical for the disadvantaged populations from remote areas that rely on subsistence agriculture and fisheries, and are uniquely vulnerable to long-term heavy metal exposure. At the landscape scale, we predict multiple negative impacts, ranging from alterations of the genetic diversity of fish populations to long-term vegetation loss and poor regeneration in contaminated areas. Consequently, compromised soil stability and runoff control will increase the risk of further geomorphologic disturbance, including landslides, bank failure and mass movements. We propose spatially explicit long-term monitoring frameworks and priority mitigation measures to cope with acute and chronic risks. We posit that, from a national perspective, disastrous impacts like that of Doce River may become more frequent, given the recent regulatory changes that undermine both institutional governance structures and enforcement of environmental regulation.

Introduction

On November 5th, 2015, Brazil experienced its worst ecological disaster when an iron mine dam (Fundão dam) failed in the municipality of Mariana, State of Minas Gerais (MG), releasing metal-rich tailings waste in concentrations that endanger human and ecosystem health. Imprudent management practices by the mining company Samarco (co-owned by the Brazilian Vale and Australian BHP Billiton) caused a breach that discharged 55–62 million m^3 of iron ore tailings slurry directly into the Doce River watershed (GFT, 2015). The volume of tailings released by the Fundão Dam represents the largest tailings dam burst in modern history, exceeding magnitudes of the two previously largest incidents in the Philippines in 1982 (28 million m^3) and 1992 (32.2 million m^3) (IBAMA, 2015a). The slurry tsunami engulfed the small district of Bento Rodrigues, destroying cultural heritage dating to the 1700s, displacing its entire population (600 people) and killing at least 19 people (MB, 2016). The mine slurry filled hydrologic networks along 663.2 km of the Doce River through the states of Minas Gerais (MG), and Espirito Santo (ES) before reaching its estuary, in the city of Linhares (ES) (INPE, 2015). The disaster currently represents the longest travelled distance by tailings in a dam failure event in South America (previous record being ca. 300 km in Bolivia in 1996) (IBAMA, 2015a). Due to the action of northward ocean currents in the Atlantic, fine suspended sediments have spread through marine habitats of the Brazillian coast (Bianchini, 2016). Consequences at broader spatial scales, including international waters through the transboundary movement of suspended sediments, remain largely unknown.

The Fundão tailings dam breach can be considered one of the worst in the last century regarding the volume of tailings released to the environment and the magnitude of socio-economic and environmental damages. Current cost estimates for restoration of the threatened Brazilian Atlantic rain forest ecosystems are around 20 billion dollars (GFT, 2015). The interwoven ecological and socio-economic impacts have affected hundreds of thousands of people in 41 cities across the Doce River basin (GFT, 2015). The destruction of riparian, freshwater and marine ecosystems eliminated irreplaceable natural resources and ecological processes that support traditional livelihoods, disrupting fisheries, agriculture, tourism and provisioning of fresh water. Here, we analyze the ecological and socio-economic impacts of the incident, highlight the lessons learned and propose integrated management and policy solutions for monitoring, mitigation and prevention of future catastrophic tailings from dams in Brazil.

Impacts to landscapes and habitats

Effects on flora and aquatic habitats were severe and most likely persistent throughout the entire watershed. A few days following the disaster, analysis of surface reflectance data in Landsat-8 images allowed measurements of the extent and intensity of the damage by the released tailings. Spatial analys developed according to the protocols of the GeoForschungsZentrum-GFZ-Postdam team, Germany (Mielke et al., 2014, 2015), identified significant vegetation loss and deposition of tailings with extreme high concentration of iron along the Doce River, at altitudes ranging from 0 m on the river delta, in Resende (ES), to 950 m in Mariana (MG) (Figs. 1 and 2). The devastation impacted approximately 1469 ha of natural vegetation and 90% of the riparian habitats of the Fundão, the North Gualaxo and the Carmelo Rivers (Fig. 3).

The tailing deposits were scattered over the affected regions, reaching widths of more than 1 km in areas immediately downstream of discharges in the city of Mariana (Fig. 1). Waste slurry, sediments and enormous volumes of uprooted plant biomass filled the main downstream channels, creating irreversible damage to 663.2 km along affected watercourses (Fig. 4). The potential extent, magnitude and reversibility of the impacts of sediment deposition over pelagic habitats, coral reefs, seaweed beds, and mangroves in the affected regions of the Brazilian coast are unknown. Preliminary data have indicated that suspended sediments may have spread for up to 200 km into the ocean resulting in even broader-scale impacts on marine systems, resulting from mobility of particulate-associated contaminants (Bianchini, 2016).

The Doce River Basin has 98% of its area inserted within the Atlantic Forest biome (83,400 km^2), one of the world's 34 hotspots for biodiversity conservation due to high levels of

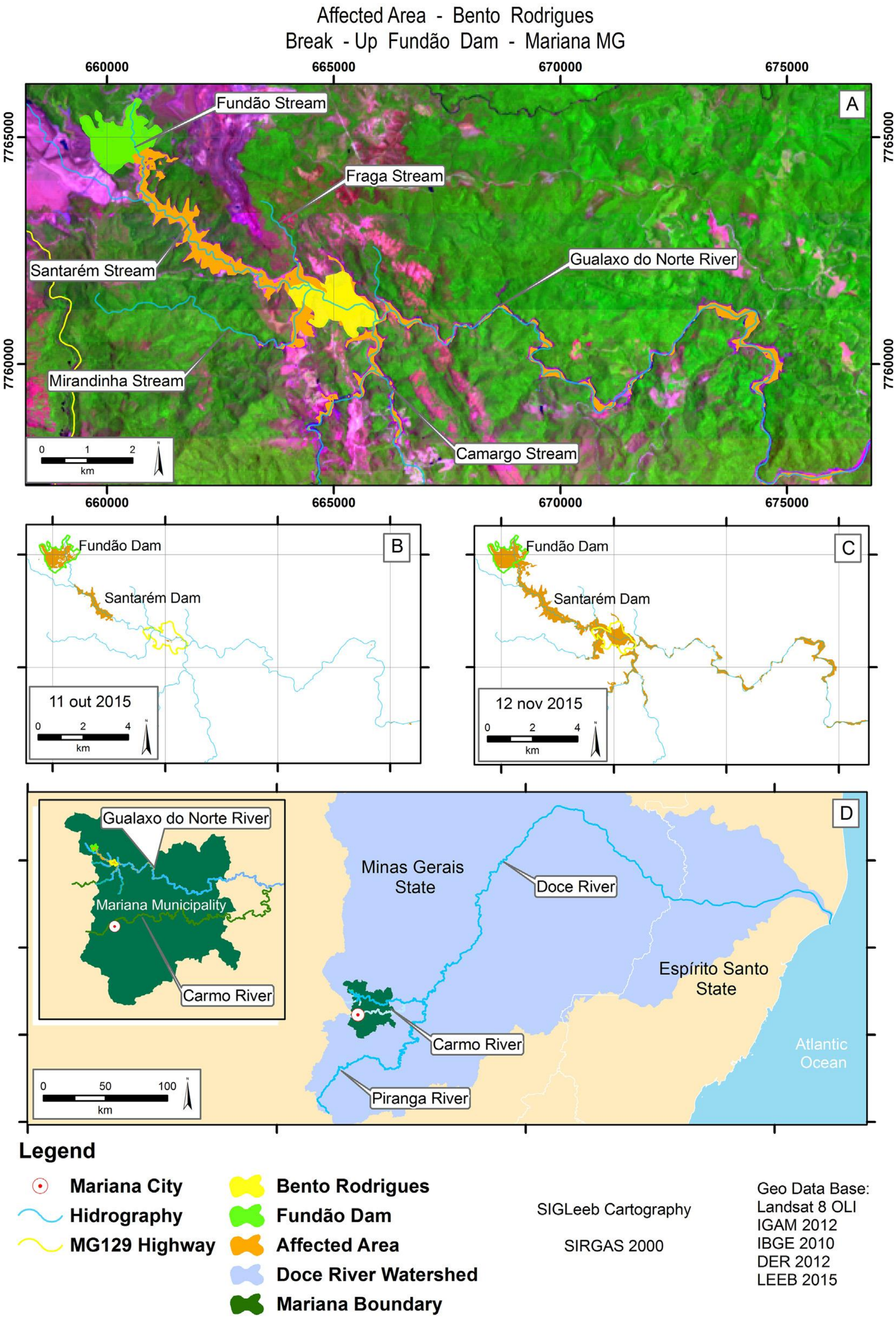

Fig. 1 – Watershed sections impacted by the Fundão Dam breach in November 2015, municipality of Mariana, Minas Gerais State, Brazil. Yellow polygon indicates the locality immediately affected by iron-ore tailings discharge. (A and B) Landsat 8OLI satellite images before and after the disaster (October 11th and November 12th, respectively). The highlighted area is equivalent to ca. 600 ha of tropical rain forests, semi-deciduous seasonal forest, and devastated agricultural lands. (C) Extent of impacts from the headwaters of the Rio Doce basin to the delta, in the Atlantic Ocean.

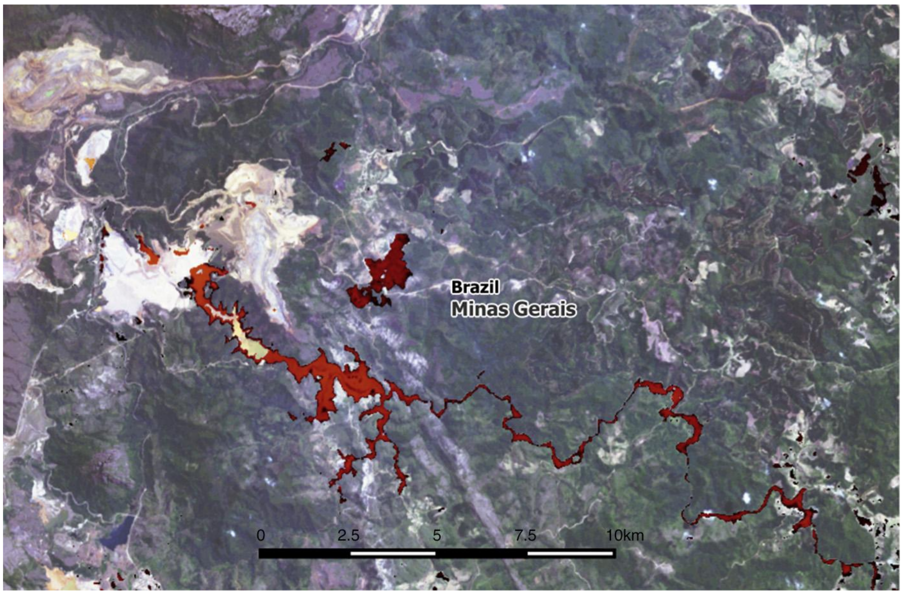

Fig. 2 – Changed Normalized Iron Feature Depth (upper 2 quartiles) as coloured true colour Landsat-8 overlay derived from differential analyses of Landsat-8 scenes from 11.10.2015 and 12.11.2015 – Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Christian Rogass, 2015.

endemism and anthropogenic alteration (Myers et al., 2000). The regions adjacent to the Doce River delta are classified as "very high" in biological importance for marine conservation, according to the Brazilian Ministry of Environment (MMA, 2007). The flow of tailings buried aquatic and riparian nursery habitats, eliminating most of the regenerative capacity of aquatic and terrestrial ecosystems. The loss of "ecological memory" underneath the thick tailings deposit layer can extend recovery time of biophysical structure, ecological function and biodiversity in affected area from decades to close to a century (Skaloš and Kašparová, 2012). Due to prolonged residence times of heavy metals released during dam bursts (Macklin et al., 1997), natural floodplain regeneration may be delayed or impeded entirely, contingent upon the extent and magnitude of contamination (Kloke et al., 1984; Bastin et al., 2002).

Impacts on aquatic fauna

Fish richness (>100 spp.) is high in the Doce River, twice the number found in Great Britain (Maitland and Campbell, 1992), with many species still unknown to science (Vieira, 2009). Six of the known species are considered at risk of extinction, according to the Brazilian list of threatened species (MMA, 2014). The impacts on ichthyofauna are of particular concern as fish communities are one of the main ecological components of the Doce River and represent a resource on which a significant portion of the local communities rely for their livelihoods (GFT, 2015; Neves et al., 2016). Entire fish populations died immediately after the discharges when the slurry buried them or clogged their gills. Preliminary data estimates the loss of significant biomass of the original fish stock in the

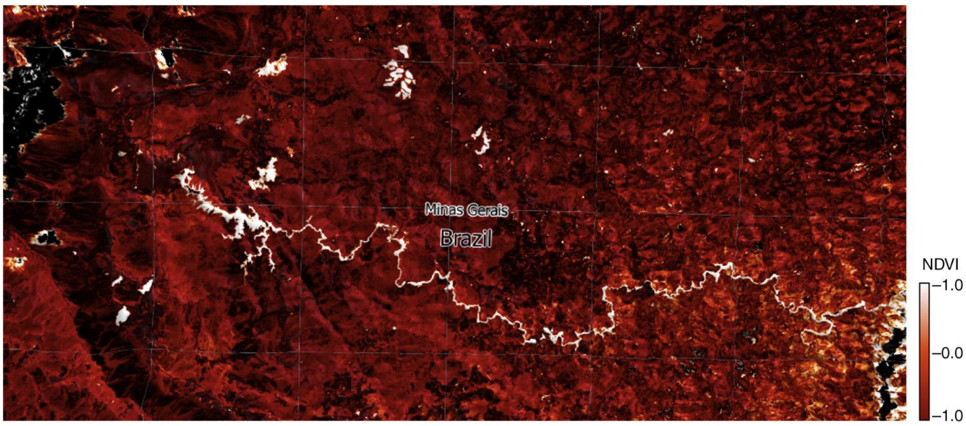

Fig. 3 – Normalized Differential Vegetation Index (NDVI) (upper quartile in white) derived from differential analysis Landsat-8 overlay, derived from differential analyses of Landsat-8 scenes from 11.10.2015 and 12.11.2015 – Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Christian Rogass, 2015.

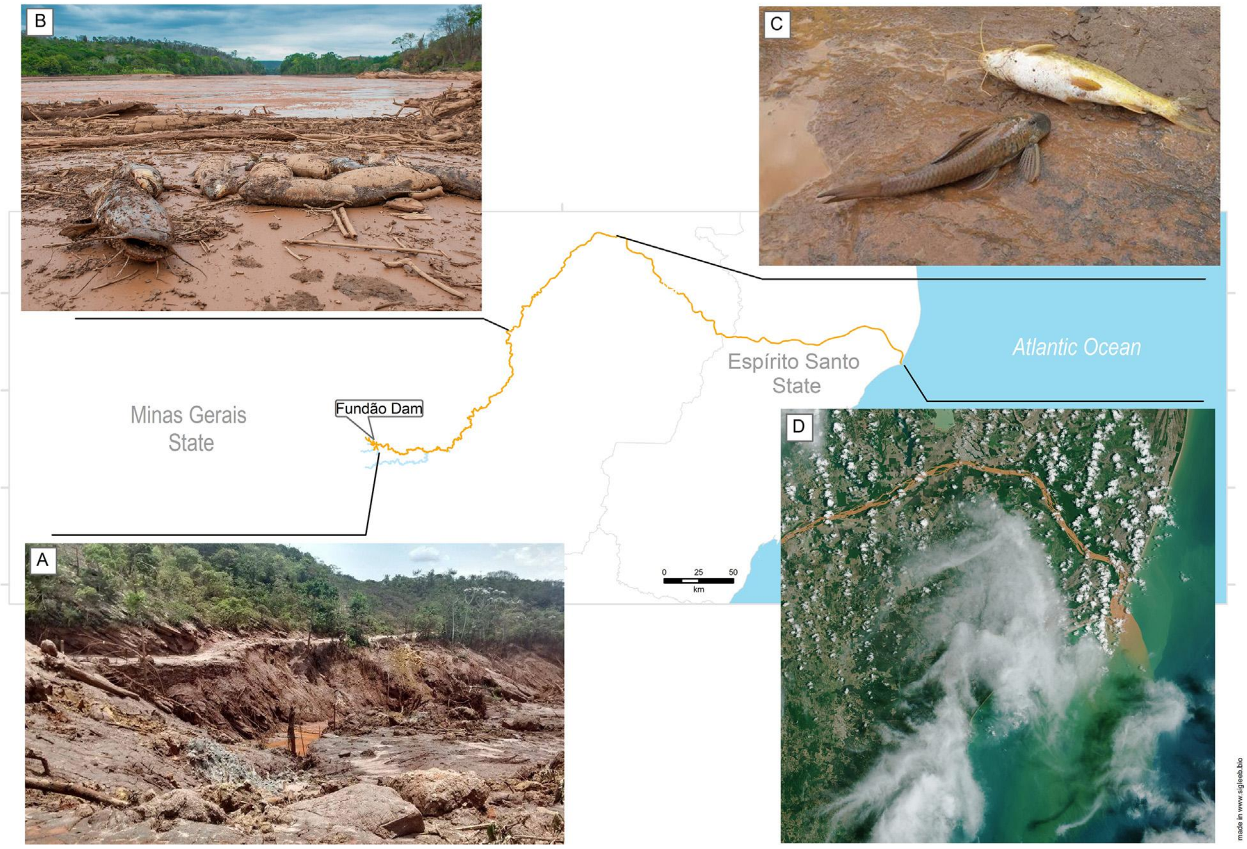

Fig. 4 – A–D Impact of the mud wave on the Doce River. (A) Bottom left picture shows the river few days after the disaster in the Camargos Municipality (photo: Pedro Ivo), (B) on the top left dead fishes nearby the Parque do Rio Doce (Photo: Elvira Nascimento), (C) top right dead fishes at Governandor Valadares (Photo: Lorraina Viana) and (D) bottom right shows an aerial photograph of the Doce River mouth 25 days after the dam burst (images downloaded at www.nasa.gov).

Doce River and marine ecosystems (GFT, 2015). Furthermore, fish species loss may be much larger than established, as current estimates did not account for long-term effects on marine fish and the communities that inhabit estuarine ecosystems during part of their lifecycles (Vieira, 2009).

While some studies consider that freshwater fish species inhabiting the Doce River are widespread in the adjacent basins (e.g. Vieira, 2009), recent molecular evidence unfolds taxonomic uncertainties that reveal higher dissimilarity (Ramirez et al., 2016). Because of the high frequency of cryptic species in the Doce River basin, the actual impact on aquatic diversity is highly unknown and many endemic undescribed species could have become extinct. One example of such concern is that of two important subsistence species inhabiting the Doce River basin: *Leporinus conirostris* and *Leporinus copelandii*. Although recorded in other coastal basins, they seem to represent complexes of cryptic species, as there is a deep genetic differentiation between specimens from Doce River basin and the adjacent Paraiba do Sul basin (Fig. 5).

Successful fish recolonization of the main channel depends on the reclamation interventions on the directly affected areas and the size, diversity and conservation status of remnant fish populations in source tributaries (Olds et al., 2012). The primary source of individuals for long-term recolonization of Doce River's main channel by aquatic biodiversity would be its lower order tributaries, such as the Santo Antonio River. However, the resilience of the whole Doce River watershed has been reduced by historic human influence such as hydroelectric dams, pollution (agricultural pesticides and sewage), and the introduction of exotic species (Barros et al., 2012). Genetic variation in remnant fish populations has been reduced by water quality, lower integrity of habitats and food webs. For example, recent molecular evidence indicates that *L. copelandii* populations from the Santo Antonio River may be already diminished (Unpublished data). Such reduced genetic diversity may be a barrier to recolonization since it reduces flexibility insurance to cope with the long-term stresses imposed by habitat disturbance (Piorski et al., 2008).

In an attempt to preserve part of the ichthyofaunal genetic bank of the Doce River, volunteers implemented the so-called Noah's Ark plan, an *ex situ* emergency conservation action to salvage specimens before the arrival of the wave of sediments (Escobar, 2015). However, due to the extreme urgency and limited resources, salvage actions occurred at just a few sites along the main channel and lacked a systematic design to assure safeguarding representative genetic variation of multiple species.

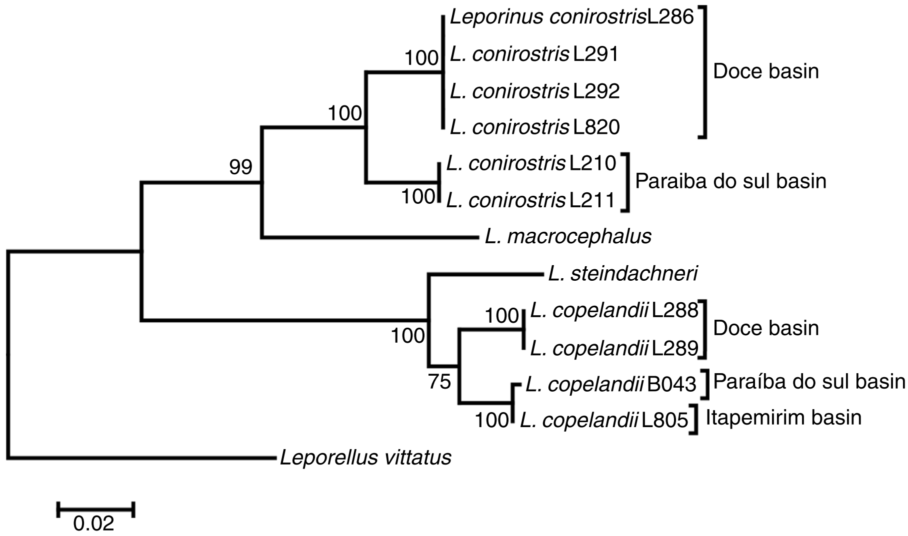

Fig. 5 – Neighbour-joining (NJ) tree obtained by COI gene analysis using K2p in Mega 6.0. The number in node corresponds to bootstrap value. *Leporinus macrocephalus, L. steindachneri* and *Leporellus vittatus* are outgroups.

Socioeconomic impacts and human health risks

The Brazilian government presented a report with the first estimate of the economic damages caused by the dam failure (GFT, 2015). Material and environmental losses were estimated to be over 20 billion dollars. The interruption of the mining activity will severely affect local economies of 37 villages and cities due to reduced royalties and tax revenues along the coming years (GFT, 2015). Tragically, some impacts are irreversible (e.g. human lives, ecosystem integrity and ecological processes, landscape aesthetics and cultural values, the colonial heritage of Bento Rodrigues village, etc.). Hence, consensus surrounding priorities, institutional roles and responsibilities regarding damage compensation still require extensive, long-term dialogue and consultations among all stakeholders (see also Neves et al., 2016).

The immediate discharge from the Fundão Dam devastated the colonial district of Bento Rodrigues (IBAMA, 2015a,b) as the tailing deposits submerged critical water resources within the Fundão micro-basin (Mirandinha, Fraga, and Camargo Creeks; Fig. 1). Despite direct effects on river channels and terrestrial ecosystems, the disruption of provisioning and regulation ecosystem services along the Doce River, poses direct and indirect impacts on livelihoods, health, and well-being of human populations extending to a much wider area of the basin (Neves et al., 2016, see also TEEB, 2010).

In the short term, 41 downstream municipalities along the margins of the Doce River lost access to fishing resources, clean water, crop production sites, hydroelectric power generation and raw materials that support local economies (Table 1). The number of affected people extends to 1 million, of which at least 300 thousand had water supply immeditely destroyed (GFT, 2015; IBAMA, 2015a; Neves et al., 2016). In the medium and long terms, the lack of regulating processes such as habitat connectivity (Villard and Metzger, 2014), erosion prevention and sediment retention by forest cover will increase the risk of biodiversity loss, floods and water contamination (Maillard and Pinheiro Santos, 2008), and will reduce nutrient cycling, microclimate regulation, and carbon storage (Pütz et al., 2014). Besides the negative effects on tangible provisioning and regulation ecosystem services, the impacts will cause losses of intangible and cultural values, such as cultural traditions, spiritual and aesthetic value of organisms, processes, and landscapes (Satterfield et al., 2013). Affected colonial and ethnic heritage, recreation parks, and subsistence and sports fishing sites, represented significant source of income and well being for the local communities (Neves et al., 2016). Severe impacts on tourism and the relational values (*sensu* Chan et al., 2016) will transcend generations following the resettlement of human populations and habitat reclamation (Russell et al., 2013).

Fishing represents an essential activity for indigenous peoples (i.e. the Krenak tribe) and has supported traditional communities in the Doce River for centuries. Due to reliance on fisheries, local fish populations represent the largest source of subsistence and income for riverine communities, as well as a critical resource for local tourism (Ecoplan-Lume, 2010). The Fundão dam failure coincided with an ecologically important fish-spawning period (locally called *defeso*), where management practices typically ban catches to ensure sustainability of populations of commercial species. A monthly minimum wage granted to fishermen by the federal government as regular cash transfer is a compensation for the ban between November 1st and March 1st. Considering the catastrophic impacts of the Fundão Dam breach on fishing resources and sensitive spawning habitat, the Public Ministry of Labour (*Ministério Público do Trabalho*), determined the continuity of the *defeso* compensation payment by the mining company Samarco. The payment was retroactive from November 5, when the disaster happened, until the re-establishment of normal fishing activities. The subsidy compensates riverine communities and fishermen, with an addition of 20% for each dependent, and a staple products quota (*cesta básica*). More generally, fishing is a traditional way of living and source of

Table 1 – Main characteristics of the Doce River basin and key ecosystem services it provides, Minas Gerais, Brazil.

General characteristics of the Doce River basin	
River basin area	87,711 km^2
Total length of main river	600 km
Number of municipalities	229
Population	~3,294,000 inhabitants
Main economic activities	Mining, siderurgy, silviculture, agronomic
Water provisioning	109,636,053 m^3/year
Number of hydroelectric power plants operating	9 large and 21 small units
Capacity of energy generation	1230.23 MW (1.6% of hydroelectric energy of Brazil and 7.2% of Minas Gerais state)

revenue for hundreds of thousands of people across the basin, yet to date only 11,000 people currently receives this monthly subsidy (GFT, 2015).

The geochemical composition of the mine ore slurry, in association with natural background concentrations in affected hillsides, will determine loading of heavy metals to all environmental compartments of the Doce River (Borba et al., 2000; Gale et al., 2004). Although Samarco and the DNPM (National Department of Mineral Production) argue that the slurry does not contain hazardous concentrations of heavy metals, several independent studies coordinated by academics, NGOs, and state and federal environmental agencies provide evidence on the contrary. A study on water chemistry by the Minas Gerais State Water Agency (IGAM) found high levels of arsenic, cadmium, copper, chromium, nickel and mercury in water samples from the Doce River following the burst (IGAM, 2015). Another study developed in coordination with the Brazilian Navy also detected high concentration of selenium, lead, arsenic and manganese in waters of the Doce River estuary (MB, 2016). Through joint efforts by several academic institutions coordinated by the Brazilian Institute of Environment (IBAMA) and the Chico Mendes Institute of Biodiversity (ICMBio), alarming concentrations of heavy metals in water and aquatic fauna of subsistence and economic importance were identified in the estuary of the Doce River, and coral and algal reefs located in marine protected areas of ES and Bahia (BA) (Bianchini, 2016). Concentration of lead, cadmium, and arsenic exceeded the threshold guidelines in 9–115 times in water (CONAMA resolution 357, released in March 2005), fish and shrimp (ANVISA resolution 42, released in August 2013). Therefore, the contamination of the entire Doce River may lead to widespread heavy metal exposure risks by riverine and coastal communities that rely on the ecological services provided by aquatic ecosystems for subsistence livelihoods (e.g. water supply, fishing, aquaculture and irrigation) (Dellinger et al., 2012).

Heavy metals pose environmental health risks due to acute toxicity at relatively low concentration and extended residence times (Macklin et al., 2006). Heavy metals may enter the human body through direct contact, inhalation of gases or suspended particles or ingestion (Behling et al., 2014; Passos et al., 2007). Intake of heavy metals by consumption of food plants grown in metal-contaminated soil (Puschenreiter et al., 2005). Fish and shellfish from contaminated water bodies (Appleton et al., 2006), or livestock feeding on contaminated pasture (Terán-Mita et al., 2013) are the main routes of exposure to these elements (Islam et al., 2007). Biomagnification across trophic levels can persist for decades due to remobilization of sediments accumulated in depositional sinks, or ‘environmental hotspots’ (Dallinger et al., 1987; Macklin et al., 2006; Dellinger et al., 2012; Lecce & Pavlowsky, 2014). Impacts will persist as water currents dissipate and remobilize sediments, solubilizing toxic heavy metals and enhancing their bioavailability (EMBRAPA, 2015). Given these conditions, levels of contamination of fish and crops can reach values above the threshold safe intake limits, affecting several biological functions and even leading to death in extreme cases (Järup, 2003). Disproportionate health effects may afflict vulnerable populations prone to higher exposure (e.g. ethnic or lower income groups that rely on local fish) or more sensitive to health burdens (e.g. the malnourished and children) (Ackerman et al., 2015; Adger, 2006; Bose-O'Reilly et al., 2008; Ohlander et al., 2013).

Claims for rapid disaster responses conflict with the need of integrated sound planning to prevent unintended consequences that may increase risks to ecosystems and human health (Speldewinde et al., 2015). Although fishing and agriculture across affected areas in the Doce River basin are banned for an indefinite time, misguided future use and restoration designs may increase human exposure to heavy metals (Rocio et al., 2013). The harvesting of grains from edible exotic legumes (e.g. *Cajanus cajan*) planted in revegetated tailings embankments may lead to similar serious consequences to human health. Prohibition of consumption of fish from populations that eventually recolonize the system or crops grown on tailings, or irrigated with contaminated waters must be strongly enforced due to high risks of heavy metal exposure (Zhuang et al., 2014). There is an urgent need for participatory assessments to identify culturally genuine alternative livelihood opportunities and food sources for the most remote and vulnerable communities in the affected areas (Wright et al., 2015).

Modelling and monitoring impacts and contaminated site risks

In the aftermath of environmental disasters, environmental and health risk assessments are key to evaluate and quantify damages at the watershed level (Ball et al., 2013; Gergel et al., 2002). Although federal and state agencies are currently pushing forward an emergency task force to monitor the Doce River basin, there is no clear framework for a systematic and integrated assessment to inform actions for mitigation of priority impacts and forecasting future risk, neither a solid proposal for scientific studies able to fulfil the gap of knowledge on ecologic functioning of remaining pristine locations in the basin, from where a plan for long term research should be built up from. For instance, a multi-disciplinary and geographically representative modelling framework is urgently needed to capture the effects of the Fundão Dam breach on multiple spatial and temporal scales as ecological hierarchies (e.g. landscapes, ecosystems, habitats, populations and individuals) and dimensions (e.g. ecological, social and psychological) (Squires and Dubé, 2013; Harfoot et al., 2014).

At the landscape scale, mapping and characterizing contaminated sites based on field assessments is key to identify the risks and hazards resulting from transport and bioaccumulation of heavy metals (Freudenburg et al., 2008). The results of comprehensive geochemical analysis of heavy metal concentration in different environmental compartments (i.e. water, sediments, and trophic cascades) allow the quantification of significant risks of exposure (e.g. target hazard quotients) for wildlife and humans (Lahr and Kooistra, 2010). Although heavy metal concentrations may indicate the depositional hotspots and bioaccumulation in certain biological endpoints, the bioavailability of the metal species in site-specific physicochemical conditions must be determined to define real risks to exposed organisms (Meech et al., 1998; Alegría-Torán et al., 2015).

Biophysical processes that influence the transport and fate of suspended sediments in mine-contaminated riverscapes are key determinants of depositional and bioaccumulation hotspots (Rowan et al., 1995; Golovko et al., 2015). Landscape features and processes such as vegetation cover, floodplain dynamics, runoff and erosion determine the horizontal and vertical migration of contaminants and hence their fate across multiple environmental compartments (Miller and Orbock Miller, 2007). Consequently, the inclusion of landscape-level structure and processes (e.g. geomorphology, hydrology, topography, geology, and river topology) may strengthen analytical protocols for investigating structure-function relationships to delineate predictive models of dynamic contamination hotspots (Squires & Dubé, 2013; Lorenz et al., 2016). This knowledge is crucial to predict landscape legacies of contaminant hotspots across multiple geographic and temporal scales (Lecce and Pavlowsky, 2014).

Spatially explicit monitoring techniques have emerged in recent decades to identify how sediment-bound contaminants travel in contaminated rivers (Macklin et al., 2006). The 'geomorphological–geochemical approach' is a practical application recommended to assess and monitor the broad-scale and long-term dispersion patterns for the sediment-associated contaminants along rivers impacted by tailings dam failure (Macklin et al., 1997). Most of the metal-contaminated sediments released into river systems (c.a. 90%) are transported via association with particulates (Miller, 1997). Therefore, particulate-associated contaminants follow similar flow patterns as natural sediment loads in rivers. The use of time series remote sensing and aerial photography, and analysis of correlations between geomorphology classification, flood regime, flow pattern, vegetation cover, soil type, and cation exchange capacity can help identify units of erosion and deposition in mining affected rivers (Macklin et al., 2003). By inferring source-sink dynamics for contaminant mobility at the reach-level, we can model risks of co-exposure to multiple heavy metals and propose ecologically robust and cost-effective site-specific remediation along the Doce River.

The Brazilian Environmental Agency (IBAMA) started monitoring the full 663.2 km extension of the Doce River a week after the accident (13–20 November) through aerial photography (IBAMA, 2015b). While aerial photography only allows to map land use change and spread of the flood, spectral analysis are particularly suitable to quantify relative levels of damage to ecosystems such as heavy metal deposition and bioaccumulation (Horler et al., 1980; Clevers et al., 2004; Kopačková, 2014; Kopačková et al., 2014). High spectral resolution sensors can help quantify physiological surrogates as indicators of plant stress to toxic mineral contaminants (Kemper and Sommer, 2003; Choe et al., 2008), including plant pigments (i.e. chlorophyll, carotenoids, xanthophylls, and anthocyanins) (Blackburn, 2007), and leaf water content (Sims and Gamon, 2002). Radar sensors are a highly promising technology to estimate and monitor the extension of the spill in aquatic and terrestrial ecosystems, based on water density and soil moisture, respectively (Clevers et al., 2004). Moreover, radars are insensitive to clouds and can acquire data at night, expanding the possibilities of retrieving information of the area.

An even worse tsunami: law relaxation over poor environmental performance

In light of the existing 730 active tailing dams operating only in the Minas Gerais State (FEAM, 2014), the Fundão dam failure is a hard lesson about the extreme risks and uncertainties associated with over-reliance on inconsistent impact assessments and self-auditing by the mining industry in Brazil. This unprecedented tragedy in the country's history could have been avoided if basic engineering precautionary measures were fully adopted (Morgerstern et al., 2016). However, law relaxation and environmental licensing that enables lower oversight and lower liability by mining companies is the current norm in recent Brazilian legislation (Ferreira et al., 2014).

Despite the reputation as a global leader in conservation of biodiversity (mainly in the Amazon region), for the past eight years the Brazilian government has taken poor decisions in environmental policy that jeopardize biodiversity, ecosystems, traditional ways of living and ecosystem services on the grounds of economic development. Blatant examples of this tendency are common in Brazilian recent legislative activity. The New Forest Code gave amnesty to landowners that deforested and decreased the mandatory private reserves (Soares-Filho et al., 2014). Recently, a new framework for mining was proposed to the Brazilian Senate, aiming at boosting mining activity by exempting large infrastructure projects of strategic interest from conducting Environmental Impact Assessments (EIA) (Meira et al., 2016). All these fallback regulation changes illustrate how the country's regulators easily bend to economic and political interests and allow nearly unlimited development.

Undermining consolidated environmental regulations by intensifying anthropogenic developments over areas of biological concern and hazard prevention can have profound effects on the likelihood of occurrence of disasters or the severity of the resulting impacts (Freudenburg et al., 2008). The Mariana tragedy is a hard lesson underscoring why environmental legislation should tighten control over dam construction and monitoring, and not the other way around. Ironically, just 20 days after the tragedy, the government of Minas Gerais established a new law that excludes the *Ministério Público Federal* of any activity referring to environmental licensing. Claiming for a less bureaucratic and faster licensing, the law alters bill 2.946/2015, empowering some governmental and private institutions and greatly reducing public participation in licensing process.

The loose enforcement of national and state environmental regulations of the mining sector in Brazil, coupled with the peripheral approach towards management of Tailings Storage Facilities (TSF) by mining companies have created a large liability portfolio in the state of Minas Gerais, home of most of the country's mining activity (Labonne, 2016). The investment on maintenance and surveillance of TSF has historically been a lower priority for mining companies, as this represents fixed operational costs of the business (i.e. do not generate revenues) (Davies, 2002). Several technical flaws in the licensing and monitoring frameworks lead to under-appreciation of risks presented by tailings dams, increasing risks of catastrophic ecological and socioeconomic impacts across whole watersheds, as observed in the Fundão event (Bowker and Chambers, 2015).

The vast majority of the environmental assessments understates ecological and socioeconomic impacts of tailing dams and do not account for downstream effects in case of a failure. The high frequency of tailing dam failures throughout Minas Gerais evidences the poor oversight and lower rigidity in environmental assessment. In the last three decades, seven dams collapsed causing human fatalities in the State. A 2014 report by the environmental agency of Minas Gerais, the *Fundação Estadual do Meio Ambiente* (FEAM) highlighted the risks associated with the operating tailing dams scattered over the State. According to FEAM's report, nearly half of 735 dams in the state are of potentially high risk to downstream human settlements and ecological integrity considering their volumes and landscape contexts. FEAM classified five dams as unsafe, and 13 were not assessed due to insufficient technical data. Still, according to the FEAM report, the safety of Fundão Dam was "guaranteed by the auditor" albeit an assessment by Instituto Pristino for the Agency for Law Enforcement and Prosecution of Crimes (*Ministério Público Federal*) warned of a high-risk failure due to basic infrastructure flaws (Escobar, 2015).

Conclusions

Historical environmental disasters such as the recent dam breaches make it clear that the environmental licensing in Brazil should be moving in the opposite direction, i.e. strengthening legislation through better governance practices such as enforcement, the rule of law, corruption control, third party scrutiny of projects, and enhancement of monitoring. Stronger governance, enforcement and reliable monitoring frameworks such as proposed here would reinforce liability of proponents of high-risk projects to the unintended consequences of their operations.

Brazil is a country with continental dimensions and allegedly the guardian of the largest repository of the world's biodiversity and tropical forest. Stakeholders and the whole society should not be guided by the principles of ecological modernization in order to equalize the different interests around Brazilian natural heritage, postponing solutions in favour of just one strategy, but an instrument to foster trans-disciplinary models that not only question current development proposals, but also create new ones, immersed in values different from those of the creators of tragic realities (Coelho et al., 2013a,b; Coelho and Fernandes, 2015). Building institutional capacity for better environmental performance through strong regulatory regimes and enforcement, integrated environmental impact assessments and preventive risk monitoring is an immediate priority. By doing so, catastrophic and irreversible impacts resulting from tragedies like the one seen in Minas Gerais could be prevented or minimized securing ecological conservation, economic development and human well-being for present and future generations.

Conflicts of interest

The authors declare no conflicts of interest.

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