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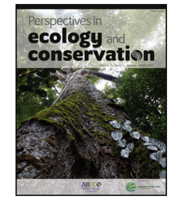

Research Letter

Forest restoration can increase the Rio Doce watershed resilience

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A B S T R A C T

Rio Doce watershed has centuries of land degradation and it was the main victim of the worst environmental disaster in Brazil's history. This process of deforestation and soil erosion could be significantly mitigated if compliance to the new Brazilian Native Vegetation Protection Law (NVPL) would be ensured. Here, we show how the percentage of forest kept in areas of permanent preservation (APP) required by the NVPL drives the overall resilience and resistance of the entire Rio Doce watershed and how it contributes to the national restoration commitments. We used water quality as a proxy for watershed resilience and resistance and we found that compliance to NVPL would require restoration of about 716 thousand hectares of riverine forest across the watershed. We found that increased forested areas improved watershed resistance and resilience during the rainy and dry seasons, respectively. Our estimates suggest that the implementation of the NVPL could improve water quality, in addition to removing 14 Gt CO_2 yr^{-1} ha^{-1} from the atmosphere. At this scale, the forest restoration effort would represent 6% of Brazil's restoration commitment. Financial feasibility of such a restoration enterprise is also achievable; at the highest possible estimate, it would compromise about 59% of the total fund proposed by the mining companies responsible for the accident. Given the low socioeconomic indicators of this basin, intervention should be designed so as to improve local livelihoods and, therefore, contribute to local adaptation and sustainable development.

Introduction

The Rio Doce is one of the main Brazilian rivers and its watershed has a long history of land degradation and unplanned water use. The Rio Doce watershed presents high rates of deforestation followed by erosion, sedimentation and eutrophication of their rivers (Consórcio ECOPLAN - LUME, 2010). In November 2015, the collapse of the Fundão dam – in the municipality of Mariana, the state of Minas Gerais – spilled 40–62 million m^3 of mining tailings in the Rio Doce. This incident has brought casualties, destroyed human settlements, impacted people's livelihoods and drastically polluted the Rio Doce (Meira et al., 2016; Neves et al., 2016). The accident was the last straw in a long-lasting degrading process, which affected the provisioning of ecosystem services for more than 1 million people (Fernandes et al., 2016). It has been estimated a loss of ecosystem services of about US$5.21 billion per year in the region (Garcia et al., 2017). Actually, forest restoration has been proposed as one of the main mechanism able to ensure water quality and quantity in the Rio Doce watershed, mainly in spring areas (Consórcio ECOPLAN - LUME, 2010; Fernandes et al., 2016; Morais et al., 2012).

Coincidently, the disaster took place almost in parallel to the UNFCCC Conference in Paris, where Brazil announced an ambitious commitment to restore 12 million hectares by 2030, which has been ratified in September 2016. The feasibility of this commitment has been discussed in previous studies (Rajao and Soares-Filho, 2015), but a set of national level policies, including recent legislation and national plans, back up such commitment (Scarano, 2017). The first one is the Native Vegetation Protection Law (the so-called New Forest Code; NVPL hereafter) that establishes the proportion of land within rural properties that must be maintained under protection or should be restored with native vegetation (Brancalion et al., 2016). The second in the National Climate Change Adaptation Plan

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(NAP), which has a strong focus on water resource management and actions related to ecosystem-based adaptation. Lastly, there is the National Policy for the Restoration of Native Vegetation (PROVEG) that announces a commitment to restore 12 million hectares by 2030. All these commitments have forest restoration as the most challenging and ambitious goal in the coming years. In particular, NVLP establishes the full protection of riparian vegetation of rivers, springs and other water sources in rural properties as areas of permanent preservation, hereafter APPs (Brancalion et al., 2016). The potential benefits and problems of the full implementation of the NVPL are still debated in the ecological literature (Metzger, 2010; Soares-Filho et al., 2014). The NVPL guaranteed amnesty for the past deforesters, as well as reduced the area of reserves in private properties compared to the former forest code (Soares-Filho et al., 2014). On the other hand, it could have some benefits like creating one of the world's major forest trading market (Soares-Filho et al., 2016). It is expected that the balance between such effects will depend on the region of its implementation and the ecological parameter studied. In the Rio Doce watershed case, water quality could be one of the main indicators of the effects of forest restoration in the region, as water quality reveals multiple integrated processes. However, it remains unclear how compliance to NVPL by restoring the existing environmental debt nearby the watercourses would drive changes in water quality of the Rio Doce watershed and how the national commitments can promote forest restoration in the region.

In this paper, we examine how compliance to the NVPL and consequent riparian forest cover restoration can influence the resilience and resistance of the Rio Doce watershed by using the water quality as a proxy and how it contributes to the national restoration commitments. We have particularly focused on watershed resistance and resilience during the rainy and the dry seasons, and discussed potential ecological and socioeconomics benefits that might result from compliance with the law. We defined resilience as the ability of the system to return to a hypothetical natural condition of water quality, while watershed resistance was defined as the ability to keep the water quality close to its average temporal behavior (see Box 1). Additionally, we discussed how multiple policy instruments could promote water quality by increasing forest restoration. Finally, we estimated the indirect contribution of the implementation of the NVPL in the Rio Doce watershed to Brazilian global commitments of forest restoration.

Methods

Study area

The Rio Doce river runs 888 km and its basin area is about 84 000 km^2, of which 86% are in the state of Minas Gerais and 14% in the state of Espírito Santo, in southeast Brazil. Climate across the watershed is warm (mean annual temperature: 18–25 °C); and rainfall is unevenly distributed with a dry season ranging from May to October (150–250 mm) and a rainy season from November to April (800–1300 mm). The watershed area lies within the limits of two global biodiversity hotspots (Mittermeier et al., 2004): 98% of its area is in the Atlantic forest and 2% in the Cerrado (Consórcio ECOPLAN - LUME, 2010).

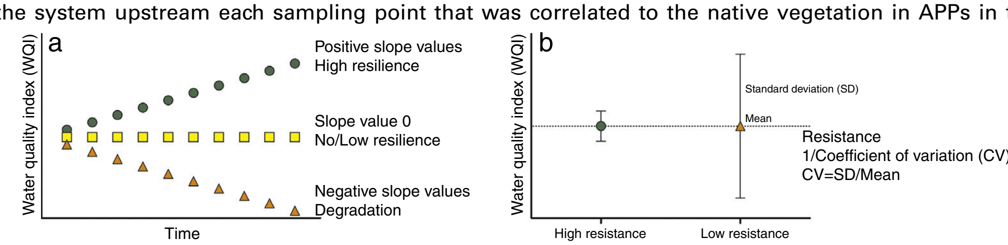
The watershed comprises 209 municipalities and is inhabited by 3.6 million people (Consórcio ECOPLAN - LUME, 2010). It provides water for domestic use, agriculture, mining, industries and power generation (Fernandes et al., 2016; Morais et al., 2012). However, the water provisioning capacity is spatially uneven across the watershed. The area has large native vegetation suppression, which promotes a soil surface susceptible to erosion, forming large volumes of sediments that are carried out to watercourses. In addition to soil erosion, the lack of wastewater treatment is the main issue encountered in the waters of the Rio Doce watershed.

Environmental debt

We mapped land use through supervised classification of RapidEye imagery (at 5 m spatial resolution) of the year 2013. The dam accident in 2015 has compromised 1469 ha of riparian vegetation that represents less than 0.2% of all APPs in the watershed. This amount of APP affected is irrelevant to the interpretation of our results. We mapped six classes: I) native forest formation, II) non-forest native formation, III) water, IV) urban areas, V) human-modified areas and VI) forestry. For the hydrological analysis, we adapted the official cartographic basis of the states of Minas Gerais and Espírito Santo to the 1:20 000 scales, using the RapidEye images as base. These adjustments contemplated three situations: i) rivers over 10 meters wide represented as lines were digitized as polygons to allow measurement of rivers' width, ii) rivers' courses were refined and iii) new water dams were included or redrawn. Vector checking and editing were done at the scale of 1:10 000, to

Box 1

We verified the behavior of water quality in the Rio Doce watershed by using the temporal dataset provided by IGAM that is fully available at the site (http://portalinfohidro.igam.mg.gov.br/). We have extracted the raw values of nine limnological variables and then calculated the water quality index (WQI) for the 64 sampling points. We have established two metrics of stability: watershed resilience (a) and watershed resistance (b) based on the WQI temporal behavior. Watershed resilience was defined as the ability of the system to return the WQI value to a natural condition, where the hypothetical WQI value is maximum (100). Thus, as WQI increase as time goes by (positive slope values) reveals high resilience. Slope value zero reveals that WQI values did not change through the sampling period (no/low resilience) while negative slope values mean a decrease in the WQI (degradation). Watershed resistance was defined as the ability to keep the WQI close to its mean temporal behavior, determined as the coefficient of variation (CV). High CV values reveal a great fragility to move from the mean behavior and a low resistance. Thus, we are describing watershed resilience and resistance as a property of the system upstream each sampling point that was correlated to the native vegetation in APPs in the same area.



produce a final map at the scale of 1:20 000. Map validation was made through 100 randomized checkpoints for all RapidEye scenes, which were compared to high-resolution satellite imagery from Google Earth (see a similar approach in Cohen et al., 2010), and reached a minimal accuracy of 95% per scene.

We calculated APPs of water bodies according to the marginal strip width values stipulated in articles 4 and 5 of the NVPL, for watercourses, lakes, lagoons, artificial reservoirs and springs (Table S1). The environmental debt was then estimated by calculating vegetation debt as the sum of areas occupied by classes IV, V and VI inside APPs. However, we did not incorporate into our calculation the differential contribution of small landowners, as predicted by the NVPL because it is still a debated point in the law.

Watershed resilience and resistance

We used the open limnologic dataset provided by IGAM (Instituto Mineiro para a Gestão das Águas; http://portalinfohidro.igam.mg.gov.br/) to determine water quality in the Rio Doce watershed. We used the water quality index (WQI), as suggested by the US – National Sanitation Foundation (ANA, 2015a). Water quality index integrates nine limnologic variables (i.e. thermotolerant coliforms, dissolved oxygen, turbidity, nitrates, total phosphorus, total suspended solids, biological oxygen demand, temperature variation and pH) to determine a single value for water quality (ANA, 2015a). Each variable has a relative contribution to establish the final index value. Several studies were undertaken using WQI (e.g. Akkoyunlu and Akiner, 2012; Lumb et al., 2011). For a detailed description of WQI, limnologic variables used, their respective contribution to the index, as well as full analytical procedure, please refer to Table S2.

We analyzed all 64 sampling points monitored by IGAM in the Rio Doce watershed (Fig. 2). Each sampling point had a different limnologic dataset since they have different sampling periods between 1997 and 2016, but all points were sampled at least 28 times (for a full description of the dataset used, see http://portalinfohidro.igam.mg.gov.br/). We did not restrict our spatiotemporal analysis to the accident for several reasons. First, we consider that the Rio Doce watershed restoration will only be complete if we use a basin approach. Second, we did not have enough data after the accident to provide a robust result for the relationship between water quality and forested areas. Third, the areas more affected by the accident were those that have the highest forest percentage in APP areas. We determined watershed resilience and resistance by verifying the temporal behavior of WQI for each sampling point (Box 1).

We verified how changes in the percentage native vegetation in the APPs predicted by the NVPL drove changes in water quality magnitude (i.e. average WQI), resilience (i.e. slope value of the correlation between WQI and time), and resistance (i.e. WQI coefficient of variation) along the Rio Doce watershed. For that, we delimitated catchment area of each sampling point in Arc Hydro for ArcGIS 10.2 (Environmental Systems Research Institute, Redlands, CA), using the SRTM digital elevation model at a 30 m spatial resolution. Then, we calculated the percentage native vegetation in APPs upstream each sampling point and correlated them with WQI magnitude, resilience and resistance. We also compared the relative effect of the native vegetation in APPs during the dry and the rainy season. For the rainy season analysis, we only used data samplings from November to April. For

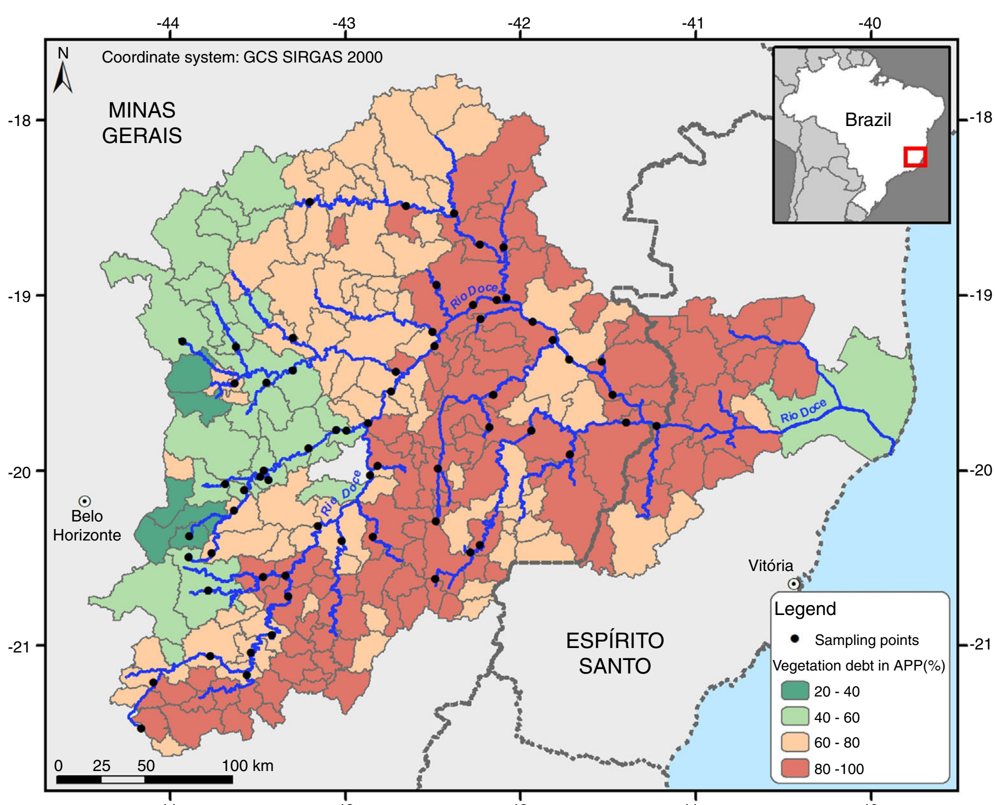


Fig. 1. Environmental debt in the Rio Doce watershed based on the areas of permanent protection (APPs) predicted by the Native Vegetation Protection Law (NVPL). The environmental debt was estimated by forestry, urban and anthropic uses in the riparian area and it sums 71%. Points in the map represent the 64 areas monitored by IGAM (Instituto Mineiro para a Gestão das Águas) that were used in the present study to determine water quality behavior in the last decades.

the dry season analysis, we used data samplings from May to October.

Effects of the implementation of the NVLP

We estimated costs to restore all native vegetation on APPs predicted by the NVPL based on estimated costs to restore the Atlantic forest, US$ 5000 ha^{-1} (Brancalion et al., 2012). Then, we estimated the carbon sequestration that would result from the implementation of the NVPL in the Rio Doce watershed based on average estimates for Atlantic forest areas, 13.6 ton yr^{-1} ha^{-1} (SOS Mata Atlântica; https://www.sosma.org.br/13135/). The increase in the watershed resilience and resistance were estimated based on the equation that describes the correlation between the WQI slope values and 1/CV values and the percentage native vegetation in APPs, respectively.

Results

The Rio Doce watershed lost historically 71% of its native vegetation cover (Fig. 1). Such deforestation has also affected riparian areas that by law are required to be protected within APPs. The deficit in APPs is of ca. 716 364 hectares of native vegetation, which is equivalent to 71% of the total APP due area (Fig. 1). This percentage was based on the riparian vegetation in hydric APPs as predicted by the NVPL in the whole watershed. Our estimates do not include hilltops and legal reserves. Most of the environmental debt is concentrated in the lower and middle Rio Doce (Fig. 1), nearby the most populous city in the region: Governador Valadares.

Average WQI for the Rio Doce watershed, considering all sampling points in all periods, was 65.2 ± 4.97 (mean ± SD). We observed an increased WQI during the dry season (WQI = 68.5 ± 5.42; mean ± SD) when compared to the rainy season (WQI = 61.6 ± 5.01). However, some regions in the watershed, such as the region downstream the Caratinga river had WQI values lower than 50 (48.5 during dry season; 45.2 during rainy season; 47 for all samplings), which means poor conditions in which conventional water treatment is not enough to allow human use (Lumb et al., 2011). On the other hand, sampling points close to springs had the highest WQI values, such as the observed for the Maquiné river (74.2 during the dry season; 74.3 during the rainy season; and 74.3 for all samplings). Table S3 shows complete results.

Percentage of native vegetation cover in APPs did not provide any significant change in the magnitude of WQI values (Fig. 2a). However, the percentage of native riparian vegetation increased watershed resilience during the dry season. Although resilience was almost three-fold higher during the rainy season, we did not observe a significant effect of riparian vegetation on resilience during this period. Considering all sampling periods, those samples holding at least 50% of upstream native vegetation in APPs (as required by NVPL) increased their WQI, on average, twice as faster than observed in other samples (Fig. 2). Considering the dry season, this pattern is even stronger; samples in places holding at least 50% of their upstream native vegetation cover increased their WQI three-fold faster than other regions (slope values: 0.24 versus 0.08). We also found that the higher the amount of native vegetation cover the higher the resistance of the watershed during the rainy season. Taking only those samples in which upstream riparian vegetation was lower than 50%, their coefficient of variation was 19% higher than the values observed in samples holding at least 50% of the riparian vegetation required by the NVPL.

Costs to restore the whole vegetation debt of the watershed were estimated around US$ 3.6 billion or 59% of the ca. 6.1 billion dollar fund proposed by Fundação Renova, the consortia formed by the companies Samarco, Vale and BHP after the Fundão dam disaster.[1] The implementation of the APPs required by the NVLP on the Rio Doce watershed will contribute to achieving 6% of the national target established by the Brazilian government, although this watershed represents less than 0.001% of the country area. Consequently, this restoration effort would promote sequestration of 14 Gt CO_2 yr^{-1} ha^{-1}. Finally, we found that restoration at this scale would increase watershed resilience four folds its actual condition and decrease 25% its coefficient of variation.

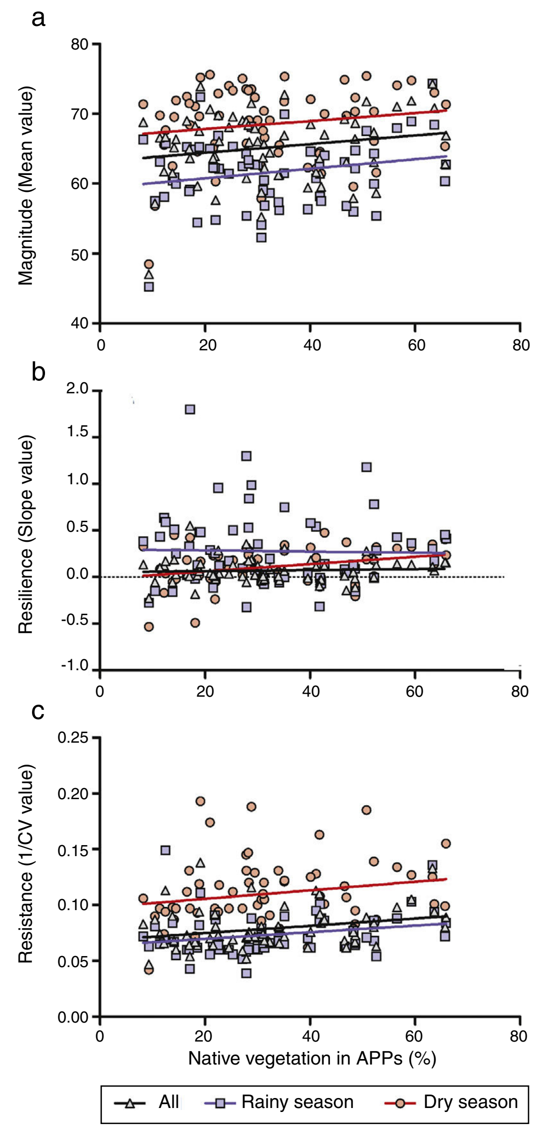


Fig. 2. Effects of percentage native vegetation in APPs on water quality magnitude (a), watershed resilience (b) and watershed resistance (c) in the Rio Doce watershed. Water quality index (WQI) was determined as proposed by the National Sanitation Foundation – USA and by using the IGAM open dataset (portalinfohidro.igam.mg.gov.br). Water quality magnitude (mean value), watershed resilience (slope value) and watershed resistance (1/coefficient of variation value) were determined through the temporal behavior of each sampling. Percentage native vegetation in APPs was determined based on the land use upstream each sampling point. Significant correlations were observed for the resilience of WQI in the dry season and the resistance of WQI in the rainy season. For full description and stats of the analysis performed, see Supplementary Material.

[1] The Brazilian justice extended the deadline for Samarco, Vale and BHP to pay the fine for three times and the full value to be paid is still debated. These values were estimated based on the first values proposed by Fundação Renova.

Discussion

Compliance with the Brazilian NVPL through legal protection or restoration of riparian vegetation could increase both resistance and resilience of Rio Doce watershed. Despite the history of forest, soil, and water degradation in the watershed, coupled with the recent environmental tragedy, our results echo previous studies showing that restoration is an important mechanism to ensure water quality (Sáenz et al., 2016). In the Rio Doce watershed, we demonstrated that forest restoration might ensure water provisioning by increasing the resistance and resilience of water quality, during the rainy and dry season, respectively.

Our analysis demonstrated that increases in the percentage of riparian vegetation cover decreased the variability in water quality during the rainy season. Considerable changes in rainfall dynamics are predicted for the Rio Doce watershed area, including an increase in the occurrence of extreme rainfall events and a slight increase in total rainfall amounts (PBMC, 2013). Previous studies demonstrated that rainfall changes in the Atlantic forest will be an important driver of change in the behavior of aquatic ecosystems (Pires et al., 2017, 2016). During the rainy season, the surface drainage carries out several compounds to water bodies, making the riparian vegetation extremely important in buffering such effect (Klapprath and Johnston, 2000). On the other hand, during the dry season, restored riparian vegetation enhanced watershed resilience, as shown by the slight increase in water quality over the last decade (see positive slope values, Fig. 2). We suggest that under drought conditions, evapotranspiration increases vegetation demand for water, which causes a negative water balance decreasing river flow and water availability (Trisurat et al., 2016). This impact may be offset by the positive effects of forested areas in protecting soils from erosion and then increasing nutrient retention, which can increase water quality. In this way, forest restoration can have a stabilizing role in determining how changes in rainfall will actually influence water provisioning in the Rio Doce watershed.

Previous studies have reported successful initiatives of forest restoration in Atlantic forest with positive effects on multiple components of riverine systems (Attanasio et al., 2012). In terms of the accident impacts, vegetation plays a significant plus role in the recovery of biodiversity in the Rio Doce watershed. While some studies point out for the fact that tailings where composed of mud deposits, others claim that it holds high levels of toxicity (ANA, 2015b; Fernandes et al., 2016). The event has transformed the benthic region of the river in a big "desert" by suppressing the organic matter in there, the main energy source for aquatic organisms in rivers (Wallace et al., 1997). Increased riparian vegetation would increase the production of terrestrial organic matter that will reach the aquatic ecosystem, as allochthonous material (Dosskey et al., 2010; Wallace et al., 1997), recomposing the necessary conditions for the proper reestablishment of benthic organisms. Riparian vegetation restoration may also increase the incidence of organisms searching for suitable habitats for oviposition, increasing the organisms' recruitment (Beltrão et al., 2009).

We stress that there are many important correlating factors, such as human population density, sanitation and urbanization level in unprotected areas that could explain the great residual effect of forest cover on water quality resilience and resistance and they should be taken into account. Also, several restoration technics have been applied in the Atlantic forest and they show considerable differences in their success rates (Rodrigues et al., 2009). The success of restoration initiatives prescribed by the NVLP may be extremely dependent on the context in which they take place. We suggest that different ways to restore forest areas should be evaluated to ensure ecosystem functioning and services in the Rio Doce watershed. In urban areas, the role of vegetation to reduce the effect of runoff may be supplanted by large sewage untreated discharge in aquatic environments (ANA, 2015a; Mulligan, 2009; Tong and Chen, 2002). Thus, initiatives that integrate multiple strategies of forest restoration and the particular sanitation issues of each area in the watershed would enhance the recovery processes of the Rio Doce river basin throughout its whole length.

Municipalities inserted in the Rio Doce basin have human development indices 11% lower than the average observed in Brazil and can be classified as a poor region (see Atlas do Desenvolvimento Humano no Brasil; http://atlasbrasil.org.br/2013/). We consider that implementation of NVPL can increase income provision and promote the local economy (Brancalion et al., 2014; Ferraz et al., 2014). In this way, the implementation of NVPL will regularize the legal situation of landowners, increasing the monetary value of their land and creating new markets for forest restoration. The establishment of the APPs predicted by the NVPL in the Rio Doce watershed will promote carbon sequestration of nearly 14 Gt CO_2 yr^{-1} ha^{-1} while contemplating 6% of the total

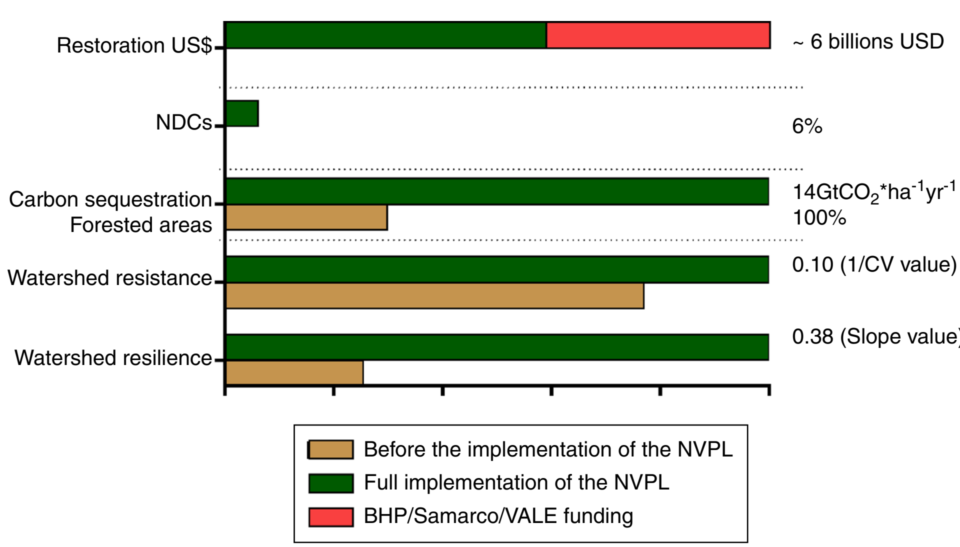


Fig. 3. Potential benefits of the implementation of the NVPL on carbon sequestration, forest areas and watershed resilience and resistance, as well as the contribution to the Brazilian NDCs. Values were estimated based on the current condition and the restoration of all areas predicted by the NVPL as APPs by considering the reforestation in Atlantic forest areas.

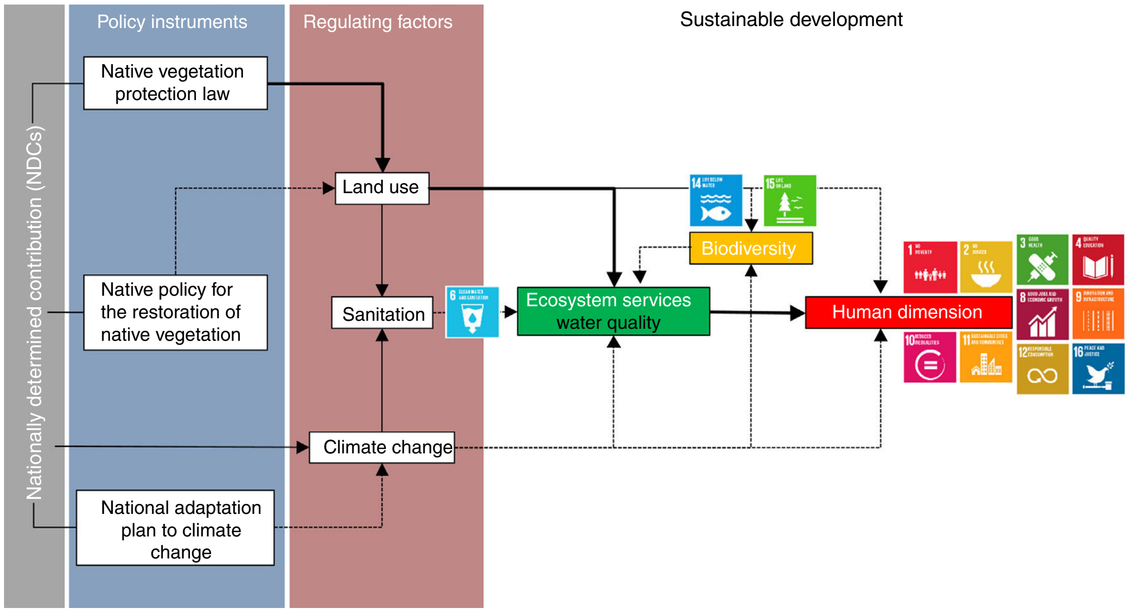


Fig. 4. Overall scenario for the implementation of the Brazilian laws and national plans on biodiversity, ecosystem services (water quality) and human dimension, considering multiple factors such as climate change, sanitation and land use. Small boxes around biodiversity, ecosystem services and human dimension terms refer to the sustainable development goals attended by the implementation of these laws. Together, it could be considered a good model for the establishment of ecosystem-based adaptation strategies (EbA) face to climate changes and the sustainable development goals (SDGs) in the country.

commitment for forest restoration established in the Brazilian NDCs (Fig. 3). Together, it would make the Rio Doce restoration a key example of ecosystem-based adaptation (Scarano, 2017; Scarano and Ceotto, 2015) by increasing income generation for populations extremely vulnerable to climate change and ensuring water quality in one of the most threatened Brazilian region (Fig. 4). Moreover, it could drive the country to reach the proposed sustainable development goals (SDGs), as the forest restoration in the Rio Doce watershed integrates multiple aspects, such as water security, biodiversity conservation and human dimension (Fig. 4).

We conclude that the restoration of riparian vegetation predicted by the NVPL may be one of the most effective mechanisms to ensure water quality for human provisioning in the Rio Doce watershed. Although our results suggest that large-scale, watershed-scale restoration could accelerate water quality improvement, restoration experience in Brazil is mostly confined to small spatial scales (Rodrigues et al., 2009). Additionally, the interaction between land use and climate changes may drastically affect the human well-being by regulating several services ecosystems provide, including water resources, in the coming years (Maneta et al., 2009; Scarano and Ceotto, 2015). Changes in water provisioning may affect several human activities and it is a challenging question, mainly in vulnerable areas such as the Rio Doce watershed area. Thus, we suggest that the full implementation of the NVPL will bring ecological, social and economic benefits and it will enable ecological restoration in one of the main Brazilian river basins. The potential success of the NVPL for the Rio Doce watershed would be strengthened if combined with other regulating factors and if several social sectors are part of the initiative, sharing the benefits arising from such endeavor.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pecon.2017.08.003.

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