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A spatially explicit index for mapping Forest Restoration Vocation (FRV) at the landscape scale: Application in the Rio Doce basin, Brazil

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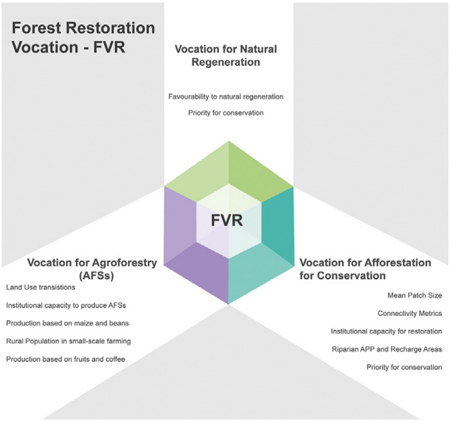
HIGHLIGHTS

- Forest Restoration Vocation (FRV) index incorporates socio-economic and institutional aspects in forest landscape restoration;
- 38% of anthropized areas have medium to high favourability for natural regeneration (passive restoration);
- 3.3 Mha with low favourability to naturally regenerate need afforestations via Agroforestry Systems (AFSs) and conservation (active restoration);
- FRV is already being adopted as a planning tool to invest US$ 300 million to restore 40 000 ha in the Rio Doce, Brazil;
- FRV is effective for monitoring forest restoration implementation across the landscape and through time.

GRAPHICAL ABSTRACT



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ABSTRACT

Effectively implementing landscape-scale forest restoration on the ground is particularly challenging. Available decision-support tools particularly lack the ability to comprehensively incorporate biophysical, social and institutional dimensions in a spatially explicit manner from the pixel to the whole landscape. In order to contribute to fulfilling this gap, this paper has two major objectives. The first is to present a spatially explicit decision-support tool for mapping Forest Restoration Vocation (FRV) that includes socio-economic and institutional aspects in

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forest landscape restoration. The second is to discuss the ways in which the FRV has been applied in the Brazilian decision-making context. The FRV was used to prioritize areas for three different restoration modalities: assisted natural regeneration (passive restoration), forest plantation with native trees to conserve biodiversity and forest plantation for agroforestry systems (active restoration). The FRV is already being adopted as a planning tool to invest R$ 1.2 billion (approx. US$ 300 million) to restore 40,000 ha in the Rio Doce, Brazil—an area corresponding to 0.05% of the area of watershed. Due to the high level of degradation of the basin, there is a need to restore 1.6 Mha via forest plantations in riparian Areas of Permanent Preservation (APPs) while 30% of APPs can be effectively restored using natural regeneration. The FRV can be effective for gauging progress and monitoring forest restoration implementation metrics across the landscape and through time. There are however still problems in effectively assessing if the investment in forest restoration will generate impact in the long term and deliver the ecosystem services society depends on.

1. Introduction

Governments, scientists, and a broad range of stakeholders have committed to several Multilevel Environmental Agreements (MEA), such as the Agenda 2030 Sustainable Development Goals (SDGs), Aichi targets (CBD), and Bonn Challenge (IUCN, 2011), as a way for moving from unfavourable development trends that, in the context of global environmental change, have been causing land degradation and the reduction of natural ecosystems, threatening the provision of ecosystem services (ES) and human well-being. Forest restoration comprises actions (passive and active) to re-instate ecological processes by accelerating the recovery of forest (or agroforestry) structure and ecological functioning for the delivery of multiple ES and human wellbeing (SER, 2020). The implementation of forest restoration, from plots to landscapes, includes approaches such as Ecological Restoration (ER), Forest Landscape Restoration (FLR) and Nature based Solutions (NbS) (see SM1)—all of which support forest restoration as a means to achieve multiple SDG, Aichi and Bonn challenge targets (Chazdon and Guariguata, 2018; Cohen-Shacham et al., 2019; Luo et al., 2019).

The benefits derived from forest restoration, and the potential that forest restoration holds to fulfil global targets and positively impact on livelihoods depends, however, on the scale and the spatial distribution of the restoration process itself (SER, 2020). The upscaling of restoration from plot to landscapes is based on the premise that forest restoration, through vegetation regrowth in strategic areas within landscape mosaics, may be of great support for improving and maintaining vital ES (Bullock et al., 2011), such as water provision and quality (Dosskey et al., 2010), soil-erosion control (Teng et al., 2019), landslide-risk control (Brander et al., 2018), carbon sequestration (Lewis et al., 2019), among others. Forest restoration that is pursued at the landscape scale is believed to positively influence the total environment: atmosphere through carbon sequestration (Lewis et al., 2019), Hydrosphere via water retention, Biosphere and biodiversity (Huang et al., 2019), Lithosphere (Teng et al., 2019), and Anthroposphere (traditional forest livelihoods). Forest restoration, if well planned for and carefully implemented, is believed to be one of the prominent pathways for moving towards biodiversity conservation (Egoh et al., 2014; Fernandez et al., 2017; Huang et al., 2019) for fostering livelihoods and wellbeing (Erbaugh and Oldekop, 2018), and for rewilding landscapes and restoring degraded ecosystems across the globe (Fernandez et al., 2017; Huang et al., 2019; Keesstra et al., 2018; Lewis et al., 2019; Luo et al., 2019; SER, 2020; Shimamoto et al., 2018).

Nevertheless, the challenges for implementing, managing and governing forest restoration at the landscape scale are immense (Mansourian, 2017; Mansourian and Parrotta, 2019; Mansourian and Sgard, 2019). Although it is already difficult to manage many of the technical aspects of plot-based restoration and the spatial issues involved when a single landowner has control over entire plots, the task is more difficult in larger landscapes with many landowners and other stakeholders, from local to regional governmental bodies, NGOs and environmental agencies (Pullar and Lamb, 2012).

Implementing forest landscape restoration is complex and tends to be operationalized through a progression of stages comprising: 1) prioritizing areas for restoration, 2) implementing and monitoring forest landscape restoration on the ground, and 3) governing restored landscapes for the long-term provision of ES. To effectively address the complexity involved in forest landscape restoration, many decision-support tools have been developed to guide decision-making. Available decision-support tools have so far been targeting restoration processes on a stepwise and modular basis (SM2). Although there is a considerable number of tools to support decision-making, those available often focus separately on 1) diagnostics (including prioritizing areas), 2) implementation (spatial planning and species selection), and 3) governance (long term financing), often neglecting, for example, implementation issues including prioritization criteria. This is problematic, as success at implementation is likely associated with allocation criteria. Most of the studies and tools for landscape restoration use biophysical criteria (biodiversity, vegetation cover, natural regeneration potential, ecosystem functions) to identify priority or target areas for restoration. Biodiversity outcomes are recurrently expected from restoration. There are a considerable number of studies that include economic criteria, such as restoration implementation and opportunity costs, or farm profitability (Vergara et al., 2017). A minority of studies emphasize social feasibility and biophysical suitability criteria altogether, but studies including institutional capacity for forest landscape restoration are clearly underrepresented.

Available restoration tools, such as Restoration Diagnostic for Successful FLR and Restoration Opportunities Assessment Methodology (ROAM), the later widely used in tropical areas of Africa, Asia and South America (IUCN and WRI, 2014), tend not to include the spatially explicit dimension appropriate to bridging decision-making and forest restoration implementation scales: while decisions are made at national and subnational regions, implementation is driven by local context and spatially explicit drivers that are not captured in the regional mapping approach that is usually undertaken. These tools although fostering stakeholder engagement tent to present difficulties at integrating biophysical with socio economic and institutional dimensions. Particularly lacking in the majority of the tools available is the ability to comprehensively incorporate biophysical, social and institutional dimensions in a spatially explicit manner from the pixel to the whole landscape. Most of the tools are so far either focussed on plots (e.g. selection of trees) or countries and regions (e.g. zoning of eco regions), without the ability to spatially target the implementation of restoration at the landscape scale. Example of the former is the Diversity for Restoration (https://www.diversityforrestoration.org/), an online tool helping decision-makers to select appropriate tree species and seed sources: this initiative, originally designed for tropical dry forest in Colombia, aimed at guiding restoration initiatives for all those interested in planting or regenerating trees, including scientists, restoration planners and practitioners, and public authorities.

In addition, most available tools (for a detailed list see SM2) are not tailored to combining nature conservation and economic livelihoods as criteria for allocating different restoration modalities. Restoration modalities range from passive (natural regeneration) to active (afforestation). Prioritization criteria and implementation issues together need to be specific to each one of the restoration modalities. Restoration via natural regeneration and restoration via agroforestry differ in many ways. These two restoration modalities need, for example, contrasting biophysical suitability and institutional arrangements in place, and these need to be mapped at finer resolutions across landscapes. Although there are spatially explicit tools available for mapping ES, these tend to map biophysical potential at scales that are not relevant for implementing restoration and overlook the integration of biophysical and socioeconomic datasets at finer spatial resolutions. This makes it difficult to use available tools to implement forest restoration, and especially in a post-disaster context (see Section 2.2).

In order to contribute to fulfilling this gap, we developed an FRV index as a landscape-scale planning tool. We applied the index in the context of the Rio Doce basin, a highly degraded region in Southeastern Brazil that has been facing long-standing unsustainable agricultural practices and, more recently, one of the world's largest environmental disasters—a large-scale mining-waste spillage due to a dam break in November 2015. Therefore, this paper has two goals: the first is to present the development of the FRV and its use for forest restoration in the post-disaster context of the Rio Doce basin; the second is to discuss implementation issues of the FRV in the Brazilian decision-making context.

The paper is structured as follows: after this Introduction (Section 1), in the Methods (Section 2) we present the study area (Section 2.1), a contextualization of the post-disaster context of the Rio Doce Basin (Section 2.2), and the research stages for developing sub-indices for three forest restoration modalities (Section 2.3): natural regeneration (Section 2.3.1), plantation of native trees with conservation purposes (Section 2.3.2), and plantation of agroforestry systems (Section 2.3.3). We also present the stakeholder-engagement process held during the study (Section 2.3.4). We then present the results for the Rio Doce case study and the implementation issues so far (Section 3). Finally, we discuss the issues involved in effectively implementing forest restoration at the landscape scale (Section 4) and summarize the conclusions (Section 5).

2. Methods

2.1. Study area

The Rio Doce is one of the largest rivers in Southeast Brazil at over 850 km long (Fig. 1). Over 3 million people spread across 229 municipalities live in the region. With a drainage area of ≈86,725 km^2, the original vegetation is composed of two biomes highly threatened by agribusiness: Atlantic forest (≈98%) and Cerrado (Brazilian savanna) (≈2%). Atlantic forest remnants occupy around 11% to 16% of the original native vegetation (Rezende et al., 2018). Over 50% of the area is anthropized (Fig. 1, yellow), comprising agriculture small scale farming, and pastures. The scarce presence of native vegetation and protected areas (Fig. 1, light green) poses a major challenge for sustainable landscape management in the region.

Considerable efforts have been made to restore the threatened Atlantic forest biome in recent decades by civil society, academia and government representatives, with the Atlantic Forest Restoration Pact as an overarching example (Brancalion et al., 2016; Melo et al., 2013). Recent studies suggest that these efforts have been effective, with more than 700,000 ha restored from 2011 to 2015 (Crouzeilles et al., 2019). There has been increasing evidence that forest restoration projects can support the improvement of particular water-related ES, however, the effects of forest restoration projects on water-related ES are likely to be different on a case-by-case basis. In central Brazil, researchers have found that riparian vegetation recovery through a Payment for Ecosystem Service (PES) program was associated with an increase in base flow, indicating aquifer recharge (Sone et al., 2019). It has also been highlighted that landscape configuration is of importance for the maintenance of water quality, being the most important driver of changes for this ES when compared to other aspects of agricultural expansion (Chaplin-Kramer et al., 2016).

FLR in this Atlantic forest biome needs to be framed in compliance with Brazilian regulations, mainly the new Forest Code (Federal Law no. 12651/2012). This law requires landowners to conserve native vegetation on their rural properties in Areas of Permanent Preservation (APPs)—including riparian areas (buffer areas of rivers and tributaries) and recharge areas (hill tops)—and with a specific portion of the land as a Legal Reserve (LR) (SM3). Forest restoration, according to the Brazilian Forest Code, can be carried out in three ways: a) facilitation of natural regeneration, b) plantations of native tree species for conserving biodiversity and c) plantation of agroforestry systems. These forest restoration strategies can be classified as ranging from passive to active. Passive restoration is based on a process of natural succession, involving minimal human intervention (Holl and Aide, 2011). This approach usually involves only the fencing of an area to allow the natural regeneration of native vegetation. Passive restoration through assisted natural recovery processes, although highly effective in certain conditions, may be very slow or even prohibitive in highly degraded ecosystems (Brancalion et al., 2017; Brancalion et al., 2016; Zwiener et al., 2014). To manage degraded lands, as is the case in a large portion the Rio Doce basin, an active restoration strategy is often required. This modality is usually carried out through silvicultural practices, such as direct seeding and planting of seedlings (Rodrigues et al., 2011; Rodrigues et al., 2009).

Thus, the combination of restoration methods across landscapes needs to take into account the potential for (or favourability to) natural regeneration to maximize benefits and reduce costs (Crouzeilles et al., 2017; Nunes et al., 2017). Natural regeneration is affected by ecological and physiographic factors, such as the availability of local resources (local resilience), seed dispersal across the surrounding forest matrix (seeds) (Rodrigues et al., 2011), and previous land-use intensity. However, in addition to physical potential, it is important to bring socio-economic factors and traditional livelihoods into FLR (Stanturf et al., 2017).

2.2. The post-disaster context and the development of the methodological approach

In 2015, the region experienced the effects of a large mining-dam break which released a wave of mud into the river basin across the states of Minas Gerais and Espírito Santo. The dam break devastated villages, caused the shutdown of water supply services in several cities, and disrupted fishing and other activities directly dependent on the river (for a detailed description of the disaster and its immediate effects, see Fernandes et al., 2016; Pires et al., 2017).

After the dam break, the federal public prosecutor, together with several government bodies and local stakeholders, reached an agreement with the mining companies to mitigate and compensate the social and environmental impacts across the basin. A new governance framework and foundation (Renova) were created to implement a public-private agreement called the TTAC (Terms of Transaction of Adjustment of Conduct). Among its goals, the TTAC established a 40,000 ha forest restoration target throughout the basin, of which 30,000 ha is to be implemented through assisted natural regeneration and 10,000 ha either through native forest plantation or agroforestry systems. The agreement stressed that restoration efforts need to impact water provision (quantity and quality), particularly, but not exclusively, for the communities directly affected by water shortages following the disaster.

In the press releases that followed the dam failure, the new governance organization felt the need to base its decisions on scientific studies to identify priority areas for restoration. To conduct the study, a *convenium* was established between Renova Foundation and two

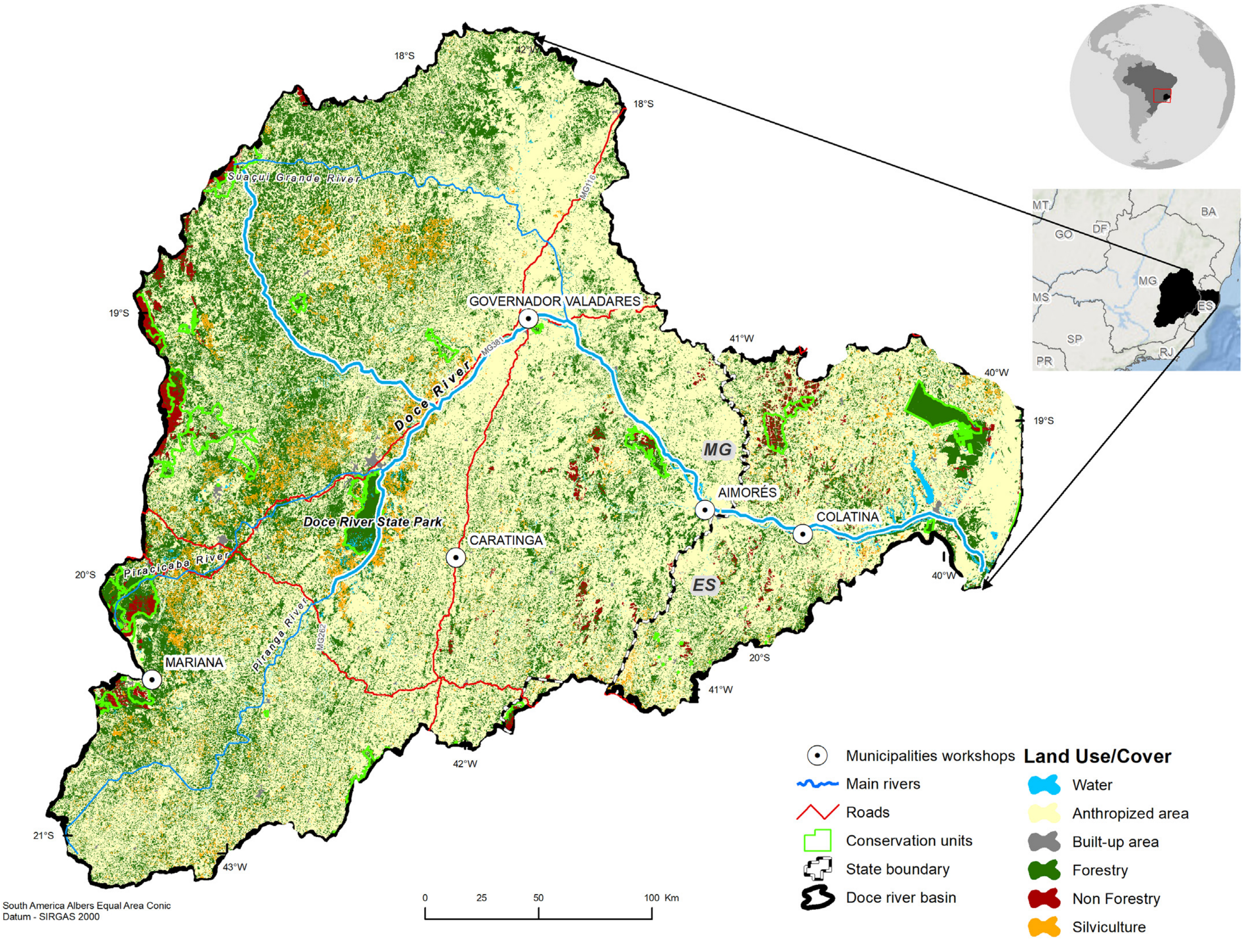


Fig. 1. Land use in the Rio Doce Basin. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

federal universities. One important demand was to classify the 229 municipalities of the basin according not only to their biophysical suitability to receive the three different restoration modalities but also to their ability to implement forest restoration initiatives successfully and maintain the investment in the medium to long term. The challenge was to use spatially explicit models and quantitative analysis to prioritize areas for receiving the three different types of restoration modality (natural regeneration, forest plantation for conservation, and plantation for agroforestry). This modelling approach used data at different resolutions from 30-meter pixel to the area of the municipality, as municipalities are considered important stakeholders for implementing governance for forest restoration at the landscape scale. The first step comprised a review of the literature on existing decision-support tools for implementing forest restoration at the landscape scale. As highlighted by a recent review by CIFOR, despite many advances in the development and application of decision-support tools in FLR, there is still a gap in tools available for the implementation of landscape-scale restoration (Chazdon and Guariguata, 2018). The toolbox available was not suited to dealing with the challenges involved in the post-disaster Rio Doce for several reasons. First, the area to be restored was devastated by the mud wave and there was a very high mediatic pressure for quick and effective responses in the short term (less than a year to start restoration on the ground). Second, we needed a spatially explicit tool able to prioritize areas for the three different types of restoration modality that incorporated, from the beginning, social and environmental dimensions into the prioritization criteria. With the collapse of the dam, the river could not be used and many livelihoods (e.g., subsistence and artisanal fishing) were lost. Thus, the inclusion of socio economic and institutional capacity is of utmost importance.

There was the need, then, to go beyond the available tools and instead devote efforts towards selecting an appropriate conceptual approach and customising the concept with the best available empirical data. Based on previous work (Carvalho-Ribeiro et al., 2013; Pinto-Correia et al., 2016), we selected the multifunctional-vocations framework (Holmes, 2006). The conceptual framing of land vocation is used to select areas that have capacity (biophysical, social and institutional) to receive different types of restoration modality, selecting areas that, with the minimum effort (both in time and financial resources), likely lead to the desired outcome by using endogenous potential (Biophysical, Social and Institutional).

2.3. Index of Forest Restoration Vocation (FRV)

Our conceptual framework builds upon the multifunctional-vocations concept by Holmes (2006) and is associated with two key assumptions: 1) modes of rural occupation are multifunctional and depend on the spatial characteristics of the landscape, including the structure and composition of the landscape mosaic, which in turn is closely associated with physiographic and ecologic characteristics of the area, and 2) socio-economic and institutional dynamics of local actors across landscapes need to be accounted for in mapping land vocation for different types of restoration modality (Carvalho-Ribeiro et al., 2013). Building on this conceptual framing, we selected variables and established classification criteria that identify and map areas with a vocation for: (i) natural regeneration, (ii) plantation with native trees for conserving biodiversity, and (iii) agroforestry systems.

The methodological approach developed through four steps (see SM3 to SM6 for a detailed description of the methods):

1) Compilation of the datasets available that can be used as variables capable of representing the assumptions of each type of land vocation. This compilation includes secondary-data collection, but also calculation and analysis of primary data (e.g., landscape metrics to quantify landscape structure and composition, listing cooperatives and number of small-farmers associations per municipality, etc.);
2) Exploratory data analysis and multivariate statistical analysis. This includes exploratory statistical and data reduction analysis including Principal Component Analysis (PCA), allowing the reduction of a broad set of variables into a lower number of components for each one of the three restoration modalities;
3) Spatially explicit modelling integrating the different dimensions to identify areas with FRV according to the three modalities;
4) Stakeholder workshops both with forest agencies and in the five major cities, one in each sub basin (see locations in Fig. 1), where the methodology and preliminary results were debated with local stakeholders.

Fig. 2 shows the datasets used for each one of the restoration modalities. Our final database consisted of 114 variables (see Database DB). We used Dinamica EGO software (http://csr.ufmg.br/dinamica/) for spatially explicit modelling. For a detailed description of the general framework and data sources, see Supplementary Material (SM3 to SM6).

2.3.1. FRV-I. Vocation for natural regeneration

The goal of this sub index is to prioritize the areas that still hold natural capital and can assist in connecting protected areas and forest remnants across the landscape matrix. Under suitable conditions, natural regeneration enables the self-organizing process of species colonization to initiate (Nunes et al., 2017). As far as implementation is concerned, conducting natural regeneration will likely involve fencing and protection, thus requiring lower labour intensity and moderate investments in time and financial resources. This modality is an example of passive restoration. The TTAC sets a target of 30,000 ha of forest restoration through natural regeneration.

Vocation for natural regeneration has two layers (Fig. 2). The favourability-for-natural-regeneration layer aggregates areas with high natural regeneration potential at the municipality scale (see SM4). The priority-for-conservation layer includes protected areas (fully protected areas and sustainable use reserves) obtained from the National Registry of Public Forests and priority areas for conservation of fauna and flora (Ministério do Meio Ambiente, 2018). By working with these two layers, we aim at prioritizing areas that still hold the ability to regenerate themselves and can be integrated with the natural vegetation of the protected-area network.

The favourability-to-natural-regeneration model was calibrated to identify areas holding potential to naturally regenerate via passive restoration and allocates each pixel of 900 m^2 (30 $*$ 30 m) a natural-regeneration-favourability index (0 to 100). This index takes into account the 1) landscape context, 2) physiographic attributes related

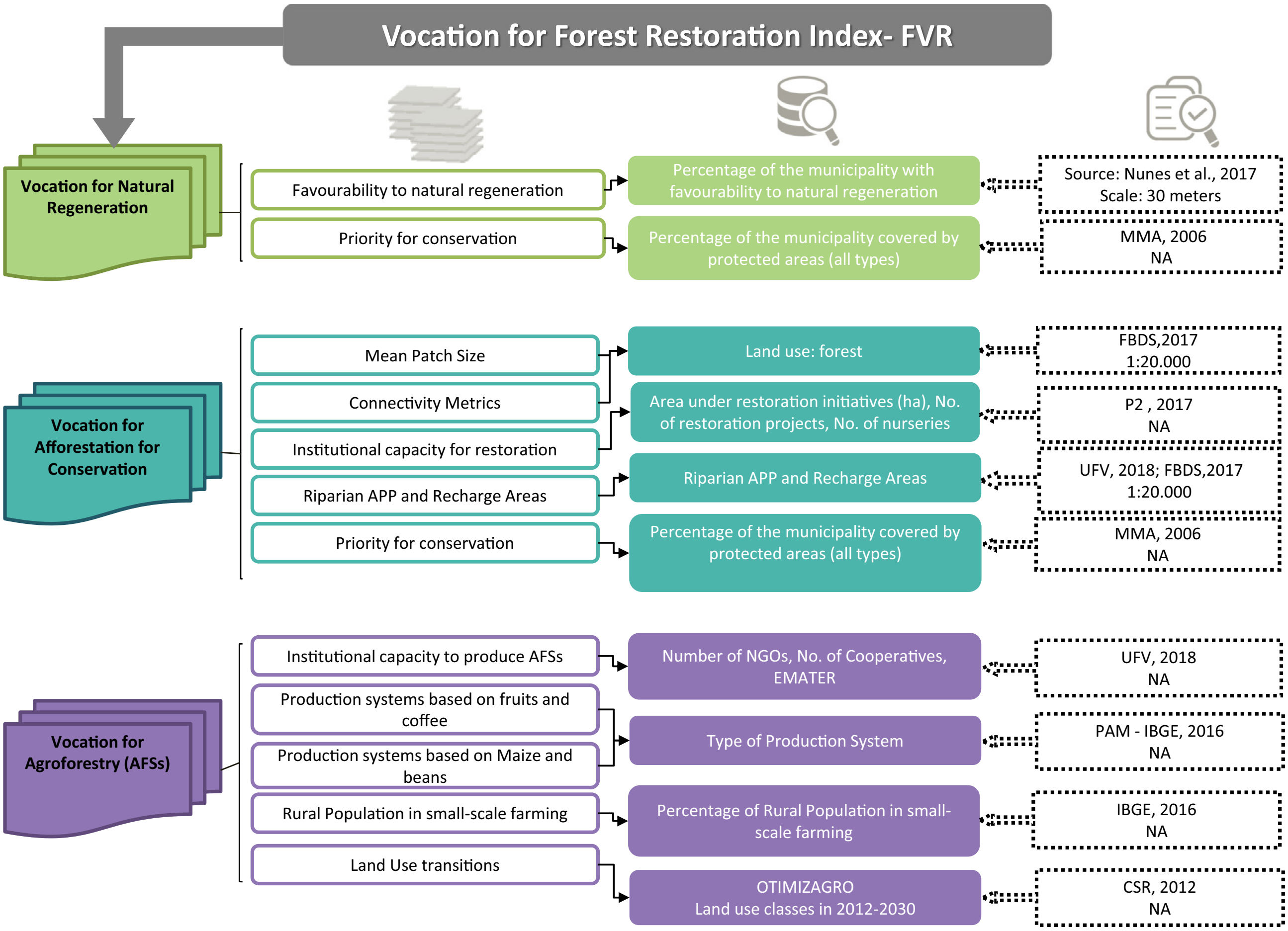


Fig. 2. FRV: Layers and variables used.

to local resilience, and 3) land use intensity (Fig. 3); this can be interpreted as the local level of effort required to encourage restoration of native vegetation through natural regeneration processes.

To estimate (1) the influence of the landscape context on the ability to naturally regenerate, we used both the land use and legal compliance maps (areas of environmental assets and liabilities according to the Brazilian forest code, namely APPs and LR) (SM3). The intersection of these maps points out suitable areas, both ecologically and in legally enforced areas, to conduct forest restoration projects in the basin. Departing from the classification of land use, for each of the 900 m^2 pixels, the set of physiographic, climatic and historical land use data that determines regional natural regeneration was analysed. We use the "area of influence" for each fragment of vegetation based on its size, identifying the cells of the map in the vicinity of the nearest fragment. Afterwards, each value is multiplied by the size of the nearest fragment in order to account for the greater chance of colonization success of propagules from larger fragments. Therefore, equidistant areas of fragments of native vegetation may have different favourability due to the influence of the spatial structure of the nearest fragment.

To estimate (2) local resilience or intrinsic capacity, we used local availability of seeds/propagules in areas with concave terrain, as those accumulate soil and water. We started by using both the land use and hill tops maps (Soares et al., 2014)to identify areas covered with native vegetation and then calculated the distance to these areas. The altimetry map was produced from ASTER images available at a resolution of 30 × 30 m (https://terra.nasa.gov/about/terra-instruments/aster) (accessed June 2020). The next step comprised the identification of relief shapes that favour natural regeneration. In general, concave forms and lower topographic areas (accumulation areas) contain higher moisture and available nutrients that can contribute to the establishment of propagules. In this way, the model calculates slope and cumulative flow in the terrain (using the elevation map generated in the previous step) and the flow direction map. The resulting map indicates the cumulative flow for each cell of the map used to identify the accumulation areas. These operations were performed through the algorithms "calc_slope_map", "calc_flow_direction_map", and "calc_cumulative_flow_map" (available in csr.ufmg.br/dinamica/). The regions with landforms classified as convergent according to the geomorphometric database of Brazil (http://www.dsr.inpe.br/topodata/) (accessed June 2020) with an average slope of less than 25 degrees are considered as areas of accumulation. The convergent forms are then reclassified into concave, rectilinear and convex forms to enhance the areas of accumulation in the concave areas and their influence on the success of natural regeneration. After identifying these areas, the model uses a 5 × 5 (150 m by 150 m) window that scans the entire map, marking the maximum areas of accumulation (accumulated flow map) and allocating its areas of influence by normalising the values of favourability based on the Euclidean distance to the maximum of accumulation. As areas with higher precipitation positively influence the natural regeneration rate (Holl and Aide, 2011), we used an annual average precipitation map to determine the influence of local climate on regeneration.

Finally, (3) land use history estimates intensity of land use, such as grazing and agricultural areas. After integrating all of the layers described above, the model generates favourability maps of the natural regeneration potential for each factor using a histogram equalization and cumulative function approaches (see SM4). Therefore, this spatially explicit model allocates areas with high and low favourability that indicate a priori the need for implementing either assisted natural regeneration (passive restoration) or afforestation methods with native species (active restoration), respectively (SM 4).

2.3.2. FRV-II. Vocation for afforestation with native species (conservation forests)

The target areas for forest plantations using native species are places with higher levels of degradation. In these areas, it is recognised that the

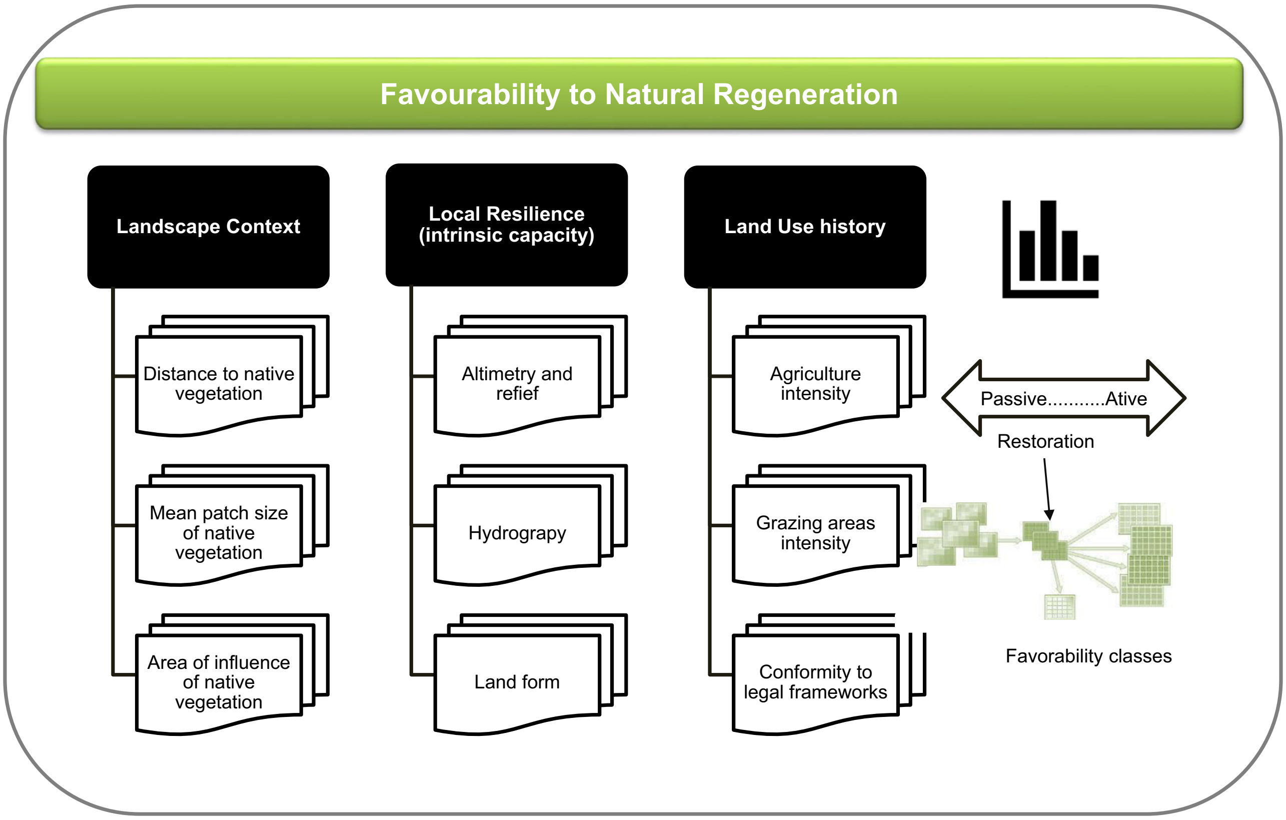


Fig. 3. Vocation for the three modalities of forest restoration: assisted natural regeneration, forest plantation with native trees to conserve biodiversity, and forest plantation for agroforestry systems.

forests will not be able to self-regenerate. Because the area is already highly degraded, effective restoration actions tend to be of an active nature, for example, using soil-conservation activities (terraces) and planting native tree species. Implementing this restoration modality on the ground demands high labour intensity and financial resources. If local people from the municipality are engaged in forest restoration, this can contribute to generating income. The TTAC sets a target of 10,000 ha for forest plantation (conservation and AFSs).

The FRV-II sub index was based on indicators related to riparian areas, APPs (including total APP area with native-forest cover), and water-recharge area with native vegetation. We used the value of the area (in ha) for both riparian (buffer areas of the river) and recharge areas (tops of the hills) of all 229 municipalities. We also calculated landscape metrics in FRAGSTAT taking as input the land use and land cover map (LULC) by *Fundação Brasileira para o Desenvolvimento Sustentável* (FBDS) (Fig. 1). In addition to APPs, the average size of forest patches in the municipality, institutional capacity for afforestation and, finally, the average distance between forest fragments (average distance to neighbour patch) as a landscape connectivity proxy (Fig. 2) were calculated. These dimensions were chosen to fulfil the assumption that reforested areas can serve as ecological corridors between protected and priority areas for conservation and other remnant forests. The layer for institutional capacity for reforestation is composed of the total area already restored in the municipality, including the number of restoration projects and the number of existing nurseries (i.e., proxies indicating that forest restoration is already in place in the municipality and therefore has institutional capital in place). Connectivity was analysed through structural metrics using Euclidean Nearest Neighbour (ENN), which calculates the mean distance (in meters) between forest patches. The average distance is measured from the smallest distance from edge to edge to the centre of the cell. For each dimension, we extracted the principal components with eigen values above 1 and classes were reclassified using the natural breaks method from 1 to 10. The principal components extracted explained over 60% of the variance of the input data (SM5).

2.3.3. FRV-III. Vocation for agroforestry systems (AFSs)

This sub index is designed to select the most suitable areas for reconciling conservationist and economic interests via food production. This forest restoration modality aims to account for knowledge that local actors have as food producers in agroecological or agroforestry systems and the existence of institutions that can support and promote agroforestry. Above all, this modality aims to include the demands of small farmers and bring forest restoration as a potential source of economic diversification to small-scale landowners by integrating the environmental recovery of APPs and LR with food production. Implementing this restoration modality on the ground demands high labour intensity and high financial resources. If local people from the municipality are engaged, this can contribute to generating income. It is designed to partially meet the goal of 10,000 ha of reforestation.

The vocation for agroforestry index aimed at including small-scale farming and traditional livelihoods into the rationale for FLR. The mapping of this vocation was based on four dimensions (Fig. 2): rural population in small scale-farm holdings as a proxy for manual labour in small-scale farming; estimated land use transitions between 2012 and 2030 (based on the analysis of 40 land use/cover classes and their transitions simulated using Otimizagro (Soares-Filho et al., 2016) for each one of the 229 municipalities); institutional capacity of the municipalities for agroforestry production (including number of agents that support local agroforestry production, e.g., cooperatives and producer associations); and data on the Municipal Agricultural Production database. In order to reduce the high number of variables (40 land uses classes Otimizagro, Soares-Filho et al., 2016) and the high number of agricultural products (agricultural production by municipality) we used PCA and extracted the principal components with eigen values above 1 whose values were reclassified using the natural breaks method from 1 to 10. In the case of production systems 2 principal components extracted represented production systems profiles based on beans and other traditional crops vs the ones based on fruits and coffee. The principal components extracted explained over 60% of the variance of the input data (SM6).

2.3.4. Stakeholder workshops

Throughout the development of the FRV, there were twelve meetings with governmental and non-governmental bodies including the Regional Forest Committees (CIF, CTFlor). There were also five stakeholder workshops for developing the methodology, presenting the preliminary results, collecting suggestions, and exploring ways to enhance the robustness of the index. Meetings with governmental and non-governmental bodies took place from May to December 2018 and the stakeholder workshops were held in July and August 2018 in five of the major cities within the basin (see locations in Fig. 1). The agenda of the meetings comprised presentations from the team developing the method (see SM 7), and participatory exercises were conducted with a broad group of stakeholders for debating the methodological framework and the variables we used.

3. Results

The spatially explicit FRV index developed in this study integrated a large socio-economic and environmental dataset to classify areas that may best benefit from different types of restoration to be implemented at the landscape scale in the Rio Doce basin.

Our results show that although the restoration of 40,000 ha in the basin is indeed one of the largest planned restoration initiatives in Brazil and perhaps the world, in practice, and due to the degraded nature of the basin, this corresponds to a small share of the degraded riparian APPs and recharge zones (Table 1).

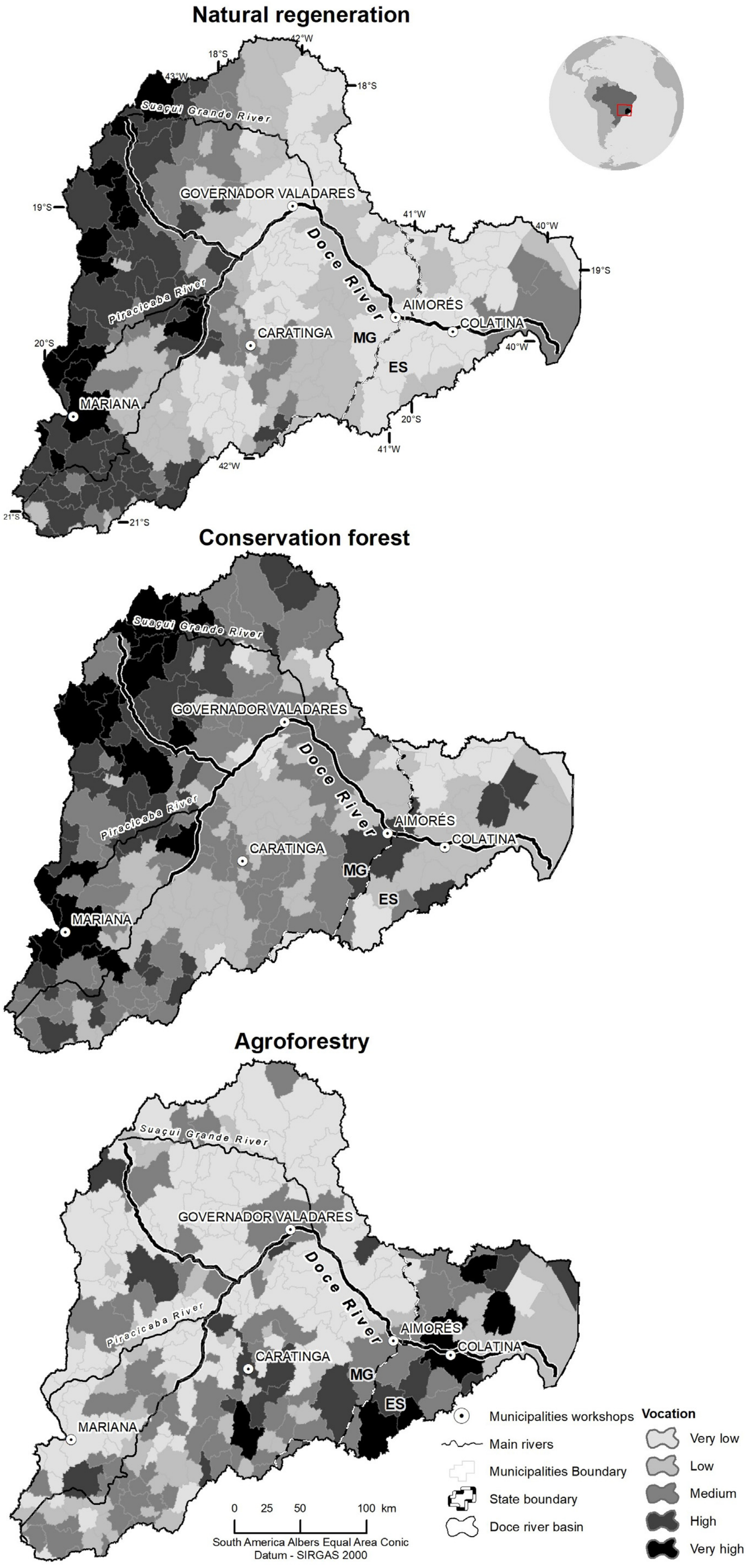
The results of the FRV show the vocation of each one of the 229 municipalities within the basin for receiving the three modalities of forest restoration: natural regeneration, afforestation with native species (conservation), and agroforestry systems (Fig. 4).

Vocation for natural regeneration was mostly allocated to the western part of the basin, while vocation for afforestation with conservation purposes was predominant in northern areas. Vocation for agroforestry, on the other hand, is prominent in the southeast portion of the basin (Fig. 4). However, most of the municipalities showed a considerable share of areas with high vocation for the three restoration modalities, thereby reinforcing the scope for planning forest restoration at the landscape scale with a multifunctional basis.

Our results show that the Rio Doce basin holds an area of 3.2 Mha with medium to high favourability for natural regeneration

Table 1
Medium to high vocation areas in the three restoration modalities.

Riparian Areas of Permanent Preservation (APP) and Recharge Areas (RAs) of medium to high vocation for natural regeneration					
	Natural regeneration	Afforestation for conservation	Agroforestry systems	Overall	Areas allocated
Riparian APP in the basin	481,325.6	688,554.5	440,315.0	1,610,195.1	
Riparian areas allocated in the priority model	7443.8 (1.5%)	11,566.4 (1.7%)	15,426.7 (3.5%)	720,266.6	34,437.0 (4.78%)
Total RA in the basin	979,563.7	1,475,304.3	925,728.4	2,161,685.3	
RA allocated in the priority model	9004.4 (0.91%)	3917.3 (0.26%)	5322.1 (0.57%)	1,307,169.7	18,243.7 (1.39%)


Natural regeneration
18°S
42°W
43°W
18°S
Suaçuí Grande River
GOVERNADOR VALADARES
19°S
41°W
40°W
19°S
Doce River
Piracicaba River
AIMORÉS
COLATINA
CARATINGA
MG
ES
20°S
40°W
MARIANA
20°S
41°W
42°W
21°S
21°S
Conservation forest
Suaçuí Grande River
GOVERNADOR VALADARES
Doce River
Piracicaba River
AIMORÉS
COLATINA
CARATINGA
MG
ES
MARIANA
Agroforestry
Suaçuí Grande River
GOVERNADOR VALADARES
Doce River
Piracicaba River
AIMORÉS
COLATINA
CARATINGA
MG
ES
MARIANA
Municipalities workshops
Main rivers
Municipalities Boundary
State boundary
Doce river basin
Vocation
Very low
Low
Medium
High
Very high
0 25 50 100 km
South America Albers Equal Area Conic
Datum - SIRGAS 2000

(favourability index above > 50), which represents 44% of available anthropized areas (without native vegetation cover). For these areas, a priori, intermediate restoration methods (assisted natural regeneration) are likely to succeed if well managed. Although these estimates still need to be refined by field work, it seems that there is considerable ground for less intensive restoration projects in the basin. However, approximately 4.3 Mha were highlighted as deeply degraded and therefore of low favourability for natural regeneration. In these areas, more active forest restoration projects based on forest plantation either with native species (for conservation purposes) or agroforestry systems are required. Considering only riparian APPs, we estimated 0.55 Mha; and of this total, 0.25 Mha were indicated as having a high favourability for natural regeneration.

As shown in Table 1, there is over 1 Mha of degraded riparian APPs that are protected by law and need to be restored in compliance with the Brazilian Forest code. Of this, 47% (481,352/1,010,709 Mha) hold medium to high vocation for natural regeneration, 68% hold medium to high vocation for forest plantation with conservation purposes, and 43% hold high vocation for agroforestry systems. One of the issues is that the 40,000 ha of this restoration project correspond to 0.05% of the land area of this highly degraded basin. Therefore, only 1.5% (7.443/481.325) of the area with medium to high vocation for natural regeneration in APPs is being implemented; the area where forests for conservation are being presently implemented corresponds to 1.7% of the APPs with medium to high vocation and 3.5% of the APPs with vocation for agroforestry. Implementation is even lower in the recharge areas,

As far as stakeholder meetings are concerned, over 400 individuals from organized civil society, government, academia, and small enterprises participated in meetings and workshops. Throughout the meetings held, we received feedback noting that the FRV responds well to the reality of the municipalities. The inclusion of variables considering the local economy as well as institutional capacity in place for the different forest restoration modalities was highly appreciated by local stakeholders. Overall, the innovation of this new index is to bring socio-economic and institutional aspects into forest restoration and ES, and stakeholders appeared to agree that this issue was fulfilled by the FRV.

During governmental meetings with federal, state, and municipal representatives, the questions raised were of a technical nature. Issues raised by governmental bodies were related to the ways in which forestation with native plants (conservation layer) (Fig. 2) was being treated in the index and demands for including other biodiversity related variables as well as functional landscape metrics into the connectivity component. After debating the need to include other biodiversity variables (including functional biodiversity metrics), we decided to instead base our assessment only on structural connectivity indexes. This was justified as, on the one hand, the focus of the restoration is not exclusively biodiversity, and, on the other, we could not independently decide on the type of biodiversity we would target (e.g., birds vs large mammals) if functional connectivity metrics were used. Other issues arose concerning the types of protected areas included as priority for the conservation layer; it was decided to include all types of protected areas, even the ones with no management plan. In parallel to the technical issues raised by the governmental bodies, meetings with local stakeholders provided valuable insights about implementation issues. Stakeholders questioned the legal status of the nurseries and whether the 32 plant nurseries inside the basin would be able to provide the number of trees needed for afforesting the whole area and the impacts that this afforestation will bring. There were also questions concerning the types of agroforestry systems that might succeed and the problems of putting agroforestry products on the market with the incipient regional market chains that these products currently have. Stakeholders called for initiatives that can help to bring new development strategies that go well beyond the low-income agro-husbandry production of the past. They particularly called for fresher planned approaches supported by new markets and financial assets for innovative rural-development initiatives in the Rio Doce basin.

4. Discussion

Forest restoration is one of the solutions for achieving commitments such as SDGs and Aichi targets, but challenges remain to implement landscape-scale forest restoration on the ground. In the absence of readily available tools, the development of the FRV was an opportunity for different stakeholders (academia, forestry governmental organizations, farmers, NGOs) to develop the premises, design and indicators for allocating different modalities of forest restoration at the landscape scale.

The development of the FRV is a step forward for enhancing effectiveness in implementing landscape-scale forest restoration. The FRV is based on a methodology that is scientifically grounded, the selection of variables was negotiated among stakeholders in a transparent way, and it was able to reconcile physical/ecological aspects of the restored landscape with social and institutional dynamics. Because of these characteristics, this work can contribute as empirical grounds for frameworks such as ER, FLR and NbS. Due to the strong focus on societal demands (generating income for small-scale farmers) and institutional capacity for different restoration modalities, the FRV is particularly suited to gauging progress towards the implementation of NbS for forest restoration (Cohen-Shacham et al., 2019; Keesstra et al., 2018).

The FRV and the variables selected for each restoration modality can also be effective for gauging progress and monitoring forest restoration implementation metrics over time. For example, metrics, such as mean area of forest patches, and connectivity, such as Euclidean distance to the nearest neighbour (ENN), can be periodically (e.g., every 10 years) calculated to assess trends in landscape connectivity. The monitoring of agreed and easily comprehensible indices used in this work can allow trend and progress assessment of FLR in the medium to long term. These indices can also be used by the municipalities as benchmarking to assess their key social (number of institutions working on restoration initiatives) and environmental (assessing how the mean area of native vegetation is changing through time) characteristics. This information is important for the municipalities in the Rio Doce area that need straightforward tools for gauging their effectiveness in land management.

Beyond this, the FRV composition in three restoration modalities (natural regeneration, forest plantation for conservation, and agroforestry) leads to a greater flexibility for municipalities to choose suitable forest restoration strategies at the landscape level. The development of the index was driven by participatory approaches including workshops and group discussions across governmental bodies, researchers and local stakeholders. Consequently, the index is already being adopted as a planning tool to channel the investment of R$ 1.2 billion (approx. US$ 300 million) to restore 40,000 ha in the basin.

The development of the FRV and its uptake into Brazilian decision making is innovative in several ways. First, the index emerged from a demand by a new governance arrangement that felt the need to ground its decisions in a quantitatively and spatially explicit way. The development of the index and the way spatially explicit modelling was used can be applied as a way to enhance the ability of established and widely used tools such as ROAM. ROAM has been used in Central and South America (e.g. Mexico, Colombia and Brazil) in Africa (e.g. Mozambique, Tanzania) and Asia (e.g. India and Indonesia) and can benefit from the integration of spatially explicit submodels from the pixel to the whole landscape scale as developed in FRV. Second, the

Fig. 4. Vocation for the three modalities of forest restoration: assisted natural regeneration, forest plantation with native trees to conserve biodiversity, and forest plantation for agroforestry systems.

workshops and expert meetings carried out throughout the project revealed that there is scope for implementing robust planning mechanisms with the capacity to put FLR into place. The index aimed at assessing institutional capacity for different forest restoration modalities that are likely to deliver more sustainable landscape-scale uses in these areas and assure that investments continue to pay off. The agroforestry sub index was particularly suited to fulfilling the demands of small-scale farmers within the region. Third, despite the mediatic post-disaster context of this study, both the scientific approach and the FRV results received constructive feedback from governmental institutions and local and regional stakeholders, indicating a promising pathway to action in this complex governance context.

An issue the FRV was not able to tackle was whether the investment will generate impact in terms of water-related ES in the long term and deliver the water quantity and quality that society depends on. As previously highlighted, there is an inherent complexity in forest-water relationships, and the effects of forest restoration projects on water-related ES need to be carefully examined in the Rio Doce context (Filoso et al., 2017). It is also important to identify other FRV caveats. By defining and spatializing the influence of variables related to the favourability for natural regeneration and agroforestry vocation, our results might underestimate the local impact of historical land use, ecosystem resilience, and the feasibility of agroforestry systems in some areas of the Atlantic Forest biome (da Silva et al., 2017; Rezende et al., 2018; Ribeiro et al., 2009). Therefore, detailed implementation studies at the local scale are still needed to better estimate site potential for natural regeneration while considering particular landowner preferences and visions (Stoms et al., 2004; Trevisan et al., 2016).

Of the forest restoration modalities, agroforestry is suited to both economic and conservation goals but is potentially more challenging to implement. One of the challenges is to create agroforestry product chains in both national and international markets. To our knowledge, international market trade agreements, for example between Europe and Brazil, that can act as a stimuli to sustainable land use and multifunctional landscape approaches are not yet in place (Hardt et al., 2015; Hardt et al., 2014; Höfer et al., 2011). Moreover, exceptions made to fair trade schemes, Multilevel Environmental agreements (MEAs) and market agreements tend to encourage agribusiness of intensive and large-scale plantations (e.g., meat, soy) associated with deforestation (Kehoe et al., 2019). Market-driven approaches and governance mechanisms that support and stimulate trade of differentiated rewilded landscapes and quality agroforestry products is lacking. There is a need for global agreements to acknowledge this issue and reinforce the types of markets that support differentiated agroforestry products well beyond the commodity markets.

A variety of approaches are available to encourage improved perceptions and incentives for agroforestry landscapes. PES has potential in Brazil, especially in light of promising innovations in trading forest certificates, yet it encounters high transaction costs and can fail to cover opportunity costs (Soares-Filho et al., 2016). Another alternative is finding commercial native species and supporting transitions to agroecological systems that can offer similar economic returns alongside outreach to increase awareness and intrinsic motivation for conservation activities (Banks-Leite et al., 2014; Trevisan et al., 2016). Some public policies have shown success: the Program for Acquiring Food has supported family farms in transitioning to agroecology via a premium and the national program for family agriculture (PRONAF) offers credit for such transitions (e.g., Coutinho and Hartmann, 2012). Certification through market and community incentives, involving standards, verification and labelling, could play a significant role, as certain tropical crops have seen substantial increases in global certified produce, such as coffee, cocoa, and palm oil (Potts et al., 2014).

However, as it stands, certification, conservation legislation and PES most often operate at producer scale and with global standards, while conservation operates at a local landscape scale; this means that farm-level conservation effects may easily be diluted or negated, and standards may be too challenging or far below existing local practice. With this in mind, linking policy, legislation and incentives to landscape-level management based on adapting models to consider the landscape as the unit of conservation could have multiple benefits, for example, for delivering ES or certifying regions for products of origin (Ghazoul et al., 2009; Kajima et al., 2017; Tscharntke et al., 2015), although operating landscape-scale schemes requires careful management of incentives and disincentives to avoid Prisoner's Dilemma or Tragedy of the Commons type problems. This suggests that present institutional arrangements and outlooks need to be enhanced to better deal with whole landscapes on a multifunctional basis planning for the delivery of multiple ES from restoration initiatives, something that the FRV presented here is contributing towards via adequately-scaled, data-driven modelling combined with institutional and public engagement.

Relatedly, the huge challenges related to large-scale restoration and governance in degraded regions such as the Rio Doce basin highlight the need to go beyond the land-sparing paradigm (Estrada-Carmona et al., 2014; Reed et al., 2016). However, in Brazil, land sparing and areas set aside for conservation are still prominent in the conservation debate in comparison to multifunctional approaches (Soares-Filho and Rajão, 2018). As such, we argue that multifunctional land vocation, including agroforestry, is a key concept to be addressed by forest restoration programs in Brazil, assuming a multifunctional landscapes paradigm (Estrada-Carmona et al., 2014; Reed et al., 2016).

5. Conclusion

This paper presents the development of a decision-support tool for effectively implementing forest restoration at the landscape scale. We applied and assessed implementation issues in the context of the Rio Doce basin, a highly degraded region in Brazil. The FRV is already being adopted as a planning tool to invest R$ 1.2 billion (approx. US$ 300 million) to restore 40,000 ha. However, this represents only 0.05% of the land area of this highly degraded basin. Therefore, only 1.5% of the area with medium to high vocation to natural regeneration in APPs have been restored; the area restored via plantations for forests for conservation corresponds to 1.7% of the APPs with medium to high vocation, and 3.5% of the APPs with vocation for agroforestry are now implemented. The FRV can be used for effectively gauging progress and monitoring forest restoration implementation metrics across the landscape and through time, as well as enhancing public and institutional orientation towards landscape-scale collaboration. There are however still problems in effectively assessing if the investments made will generate impact in the long term and deliver the water-related ES that society depends on.

CRediT authorship contribution statement

Sónia M. Carvalho Ribeiro: Conceptualization, Methodology, Writing - original draft. **Raoni Rajão:** Investigation, Conceptualization, Methodology, Writing - review & editing. **Felipe Nunes:** Project administration. **Débora Assis:** Software, Formal analysis, Visualization. **José Ambrósio Neto:** Investigation, Formal analysis. **Camilla Marcolino:** Project administration. **Leticia Lima:** Investigation, Formal analysis, Writing - review & editing. **Thomas Rickard:** Investigation, Formal analysis, Writing - review & editing. **Caroline Salomão:** Investigation, Formal analysis, Writing - review & editing. **Britaldo Soares Filho:** Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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