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GIS-based multicriteria analysis to define priority areas for forest recovery following the environmental disaster in Rio Doce Basin, Brazil

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Resumo. A floresta Atlântica Brasileira é um dos ecossistemas mais fragmentados e o mais explorado. Como as atividades de restauração são dispendiosas, a análise de decisão multicritério (MCDA) integrada ao SIG (sistema de informações geográficas) fornece um poderoso sistema de suporte de decisão espacial para produzir mapas de forma eficiente. O colapso de uma barragem de mineração em áreas de floresta atlântica, resultou na destruição de comunidades inteiras por um rio de lama e resíduos de mineração. Devido à grande extensão de áreas degradadas, uma das primeiras perguntas que abordamos neste estudo foi onde restaurar. Assim, o objetivo deste trabalho foi mapear e identificar áreas prioritárias para a recuperação florestal em uma porção da Bacia do Rio Doce (DO1). Foi utilizada a análise de decisão multicritério baseada em SIG associada ao método de combinação linear ponderada (WLC) na agregação de critérios. O resultado foi um mapa prioritário, indicando 1,73% da Bacia do Rio Doce - DO1 com alta prioridade de recuperação florestal; 5,18% com alta prioridade, 57,88% com prioridade média, 1,34% com baixo e 0.00% com prioridade muito baixa. As áreas restritas (água, vegetação nativa e áreas urbanas) representaram 33,88% da área de estudo. A metodologia proposta neste estudo pode ser aplicada em toda a extensão da Bacia do Rio Doce, bem como em outras regiões que necessitam de apoio para a tomada de decisões, como o bioma Pantanal, marcado pelo desmatamento para a expansão de pastagens.

Palavras-chave: recuperação florestal, combinação linear ponderada, análise espacial, áreas prioritárias.

Abstract. The Brazilian Atlantic forest is one of the most fragmented ecosystems and most exploited Brazilian biome. As restoration activities are expensive, multicriteria decision analysis (MCDA) integrated with GIS (geographic information system) provide a powerful spatial decision support system to efficiently produce maps. The collapse of a mining dam in a region of Brazilian Atlantic forest, resulted in the destruction of whole communities by a river of mud and mining waste. Due to the large extent of degraded areas, the first question we addressed in this study was where to restore. Thus, the objective of this study was to map and identify priority areas for forest recover in a portion of the Rio Doce Basin (DO1) that was affected by the collapse of a mining dam. We used GIS-based multicriteria decision analysis associated with the weighted linear combination (WLC) method in the aggregation of criteria. The result was a priority map, indicating 1.73% of Rio Doce Basin – DO1 with very high priority for forest recovery; 5.18% with high priority; 57.88% with medium priority; 1.34% with low and; 0.00% with very low priority. The restricted areas (water, native vegetation and urban areas) represented 33.88% of the study area. The method presented here may potentially be replicated throughout the whole Rio Doce Basin, as well as in other regions that require support for decision making in environmental planning, such as the Pantanal biome, marked by deforestation for pasture expansion.

Keywords: forest recovery, weighted linear combination, spatial analysis, priority areas.

1. Introduction

The Brazilian Atlantic Forest is a globally important ecological hotspot (Araujo et al. 2015), considered one of the most important ecoregions in the world and is a priority for biodiversity conservation (Myers et al. 2000). However, the Atlantic Forest is also one of the most fragmented ecosystems and most exploited Brazilian biome, which, for centuries, has endured timber exploitation, agricultural development, farming, exotic tree plantations, and hunting (Santos et al. 2018). This ecosystem originally covered about 150 million ha and is comprised of different types of vegetation, maintaining only 12% of its original forest cover (Ribeiro et al. 2009). The transformation of forested areas into patches, causes changes in ecosystem processes, decreasing the water quality due to soil erosion, increasing the nutrient and sediment loading in rivers (Yang et al. 2016). As restoration activities are among the most expensive conservation strategies worldwide (Holl et al. 2003), developing approaches for the prioritization of restoration efforts is a crucial task (Fernández and Morales 2016).

Multicriteria decision analysis (MCDA) is one approach that has been used effectively in the forest restoration process, as it can be used at the landscape scale, i.e. we can aggregate the criteria, which represents the critical characteristics of landscape structure (Valente et al. 2017). One of the advantages of an MCDA approach in group decisions is the capacity for calling attention to similarities or potential areas of conflict between stakeholders with different views, which results in a more complete understanding of the values held by others (Kiker et al. 2005). The integration of MCDA in a GIS (geographic information system) provides a powerful spatial decision support system which offers the opportunity to efficiently produce maps. Indeed, GIS is a powerful tool for analysing spatial data and establishing a process for decision support (Hamadouche et al. 2013). Because of their spatial aggregation functions, MCDA methods can facilitate decision making in situations where several solutions are available, various criteria must be taken into account and decision makers are in conflict (Meng and Malczewski, 2015).

The collapse of a mining dam located in a Brazilian Atlantic Forest on 5th November 2015, considered one of the biggest environmental disasters in the country's history, resulted in the destruction of whole human communities by a river of mud and mining waste. This calamity affected the Rio Gualaxo in Brazil's Mariana district, a tributary to the Rio Carmo, and ultimately the Rio Doce; waterways that supply water to a significant number of municipalities. The flood affected 600 kilometres of riverbed and destroyed human and animal lives as well as several land cover classes (such as grasslands, urban areas, and native vegetation), including permanent preservation areas (Silveira et al. 2017). Due to the large extent of degraded areas, the first question we addressed in this study was where to restore.

2. Objective

The objective of this study was to map and identify priority areas for forest recover in a portion of Atlantic Forest in the Rio Doce Basin (DO1) which was affected by the collapse of a mining dam in 2015. We used a GIS-based multicriteria decision analysis associated with the weighted linear combination (WLC) method for the aggregation of criteria.

3. Material and Methods

In Brazil's Mariana district, located in the central region of Minas Gerais (MG) state, the Rio Gualaxo, a tributary to the Rio Doce, was the main focus of this study due to the collapse of a mining dam resulted in the destruction of preservation permanent areas and forest remnants. The study area covers a portion of the Rio Doce Basin, in MG state, the DO1, where vegetation is predominantly composed of Atlantic Forest vegetation types (**Figure 1a**). The DO1 represents 24.65% of the total area of the Rio Doce Basin, totalling 14,062 km² (**Figure 1b**), and is characterized by a hilly relief and abundant tablelands. The climatic conditions are typical of humid tropical highlands (Silveira et al. 2017). The effects of the flood in the permanent preservation areas of Rio Gualaxu were clear (the main river in blue (**Figure 1c**).

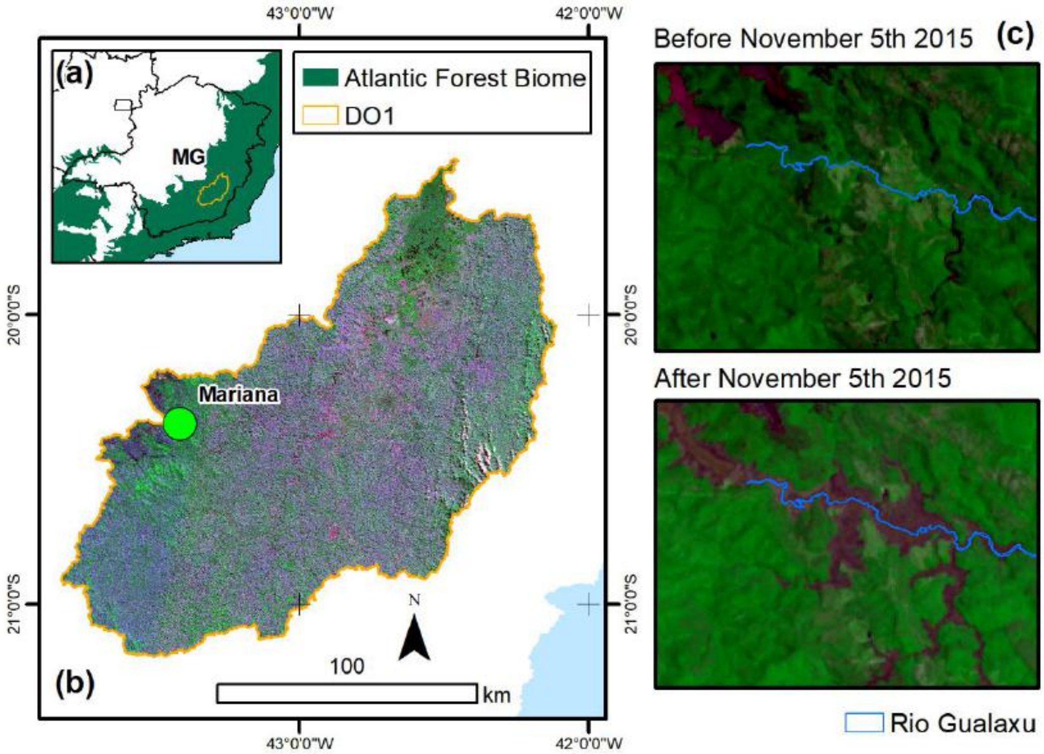

Figure 1. (a) Location of the study area (DO1) in MG state; (b) Landsat TM image R3 G2 B1 detailing the DO1 and; (c) Illustration of the effects of the flood in the permanent preservation areas of Rio Gualaxu, before and after the environmental disaster.

We used MCDA to define priority areas for forest restoration, following four (4) main steps (**Figure 2**). We employed the following data sets:

- Precipitation, acquired from WorldClim (Hijmans et al. 2005);

- Drainage network digitalized by a skilled interpreter using images from Rapid eye satellite (5 meters spatial resolution);
- Land cover map provided by Carvalho et al. (2006) manually edited by a skilled interpreter;
- Soil map (FEAM 2010);
- Digital elevation model (DEM) obtained from ALOS PALSAR.

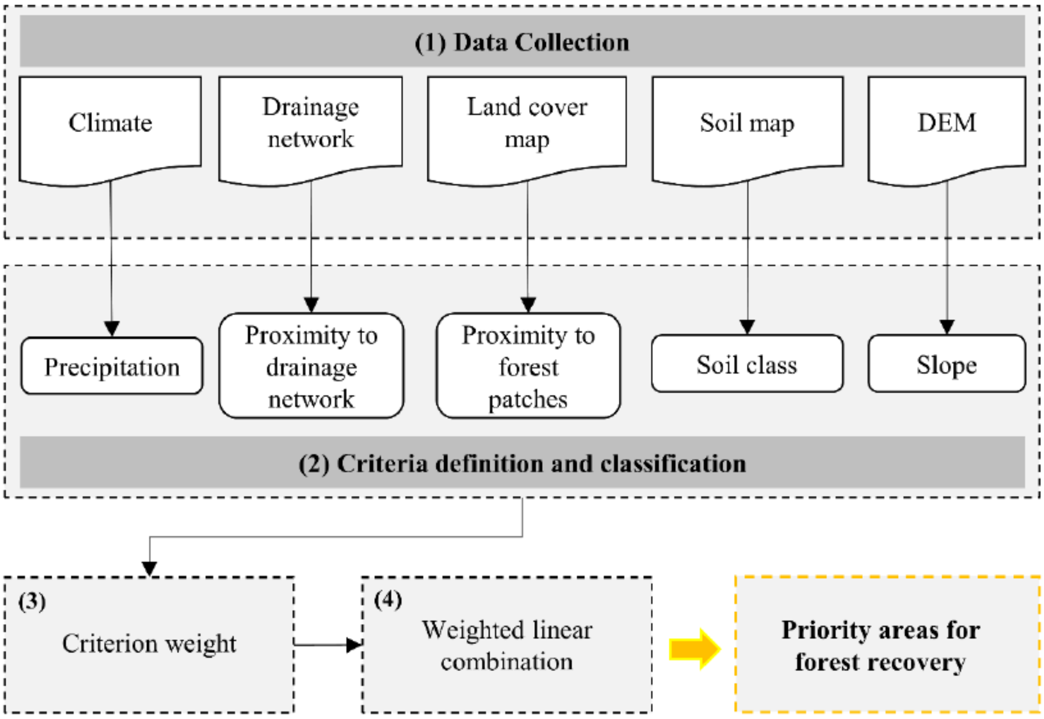

Figure 2. Methods flowchart detailing the four main steps to identify priority areas for forest recovery in a portion of the Rio Doce Basin.

The definition of criteria and classification was based on previous studies (Fernández and Morales 2016; Holl et al. 2003; Kiker et al. 2005; Meng and Malczewski 2015; Ramírez-Toro et al. 2017; Sartori 2010; Silva et al. 2017; Vettorazzi 2006; Yang et al. 2016). We used as restricted areas the land cover classes: water, native vegetation and urban areas. This means that the final map of priority areas considered only the territory within the boundaries of the Rio Doce Basin (DO1), except for areas occupied by these land cover classes.

There are a number of methods for determining weightings of criteria. The analytic hierarchy process (AHP) is a proven, effective means of dealing with complex decision making and can assist with identifying and weighting selection criteria, analysing the data collected for the criteria and expediting the decision-making process. By making pairwise comparisons at each level of the hierarchy, participants can develop relative weights, called priorities, to differentiate the importance of the criteria. The scale recommended by Saaty (1990) is from 1 to 9 (**Table 1**). The assumption is that if attribute A is absolutely more important than attribute B and is rated at 9, then B must be absolutely less important than A and is valued at 1/9. One of the advantages associated with the method is the ability to associate weights with the criteria, considering the relative importance that exists between them in the decision-making process (Valente et al. 2017).

We used Weighted Linear Combination (WLC). According to this method, the criteria are multiplied by their respective criterion weights and after they are summed. The WLC was employed in the criteria aggregation, to produce the priority map. We classified the map into five priority levels: very low, low, medium, high, and very high. We performed the analysis in the ESRI's package ArcGIS.

Table 1. The Saaty rating scale intensity.

Intensity of importance	Remark
1	Equal
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2,4,6,8	Intermediate values

4. Results and Discussion

The criteria indicated for prioritization areas for forest restoration in the DO1 were precipitation, proximity to drainage network, proximity to forest patches, soil class and slope. These criteria were first classified, ranging from 1 to 3 (**Table 2**), according to previous studies, as mentioned above. The closer to three, the higher the priority for forest recovery.

Climate variables such as precipitation control weathering directly. For example, rain weathering the rocks, and later soil is removed by water erosion. The direct impact of the droplets and the runoff are the active agents of water erosion. Thus, as the precipitation increases, the classification value increases (**Figure 3a**). We considered that areas closer to drainage networks were better suited for restoration, as water is essential to fauna and flora, to the need for greater protection of water resources and to the occurrence of leisure activities in these places. It is considered that forest cover is important for the water quality in a river basin, regardless of its distance from the elements of the drainage network, but this importance, in general, increases as the distance to the drainage network decreases (Vettorazzi 2006). At the edges of the drainage network, the forest vegetation, as well as permanent preservation areas, is one of the most important protection measures (Figure 3b).

Proximity to forest patches (**Figure 3c**) was judged to be important for forest restoration because the spatial distribution of remnants is an indicator of landscape configuration, in terms of their degree of forest fragmentation. Experts highlight forest connectivity as the only way to obtain restoration at the landscape level (Valente et al. 2017). Physical (structure, texture, permeability and density) and chemical properties of different soil types (Figure 3d) lead to different effects in the erosion process. These properties cause greater or less resistance to the action of water even in similar conditions of precipitation, topography and land cover (Bertoni and Lombardi Neto 1990). Greater attention was paid to areas with higher slopes (Figure 3e). Greater slopes mean a greater flow of water and, therefore, less water availability. These areas will be more susceptible to erosion which may be a threat to conservation and forest preservation (Rosa et al. 2000).

The criterion weights obtained are presented in **Table 3**. The CR (consistency rate) was 0.043, indicating that the matrix has a reasonable level of consistency and, that we can use the indicated criteria weights for the Rio Doce Basin – DO1 decision problem. The highest weight was obtained for proximity to drainage network criteria (0.52), indicating that the permanent preservation areas were identified as the most important areas for recuperation.

Table 2. Criteria classification. A=Precipitation (mm/monthly); B= Proximity to drainage network (m); C= Proximity to forest patches (m); D= Soil class; E=Slope (º).

A	B	C	D	E	Classification
<50	> 400	> 400	Latosoils	< 2	1
50-75	-	-	-	-	1.1
75-100	-	-	-	-	1.2
100-125	-	-	-	-	1.3
125-150	-	-	-	-	1.4
150-175	400	400		2-6	1.5
175-200	-	-	-	-	1.6
200-225	-	-	-	-	1.7
225-250	-	-	-	-	1.8
250-275	-	-	-	-	1.9
275-300	300	300	Argsoil	6-20	2
300-325	-	-	-	-	2.1
325-350	-	-	-	-	2.2
350-375	-	-	-	-	2.3
375-400	-	-	-	-	2.4
400-425	200	200	Cambisoil	20-50	2.5
425-450	-	-	-	-	2.6
450-475	-	-	-	-	2.7
475-500	-	-	-	-	2.8
500-525	-	-	-	-	2.9
>525	100	100	Neosoil	>50	3

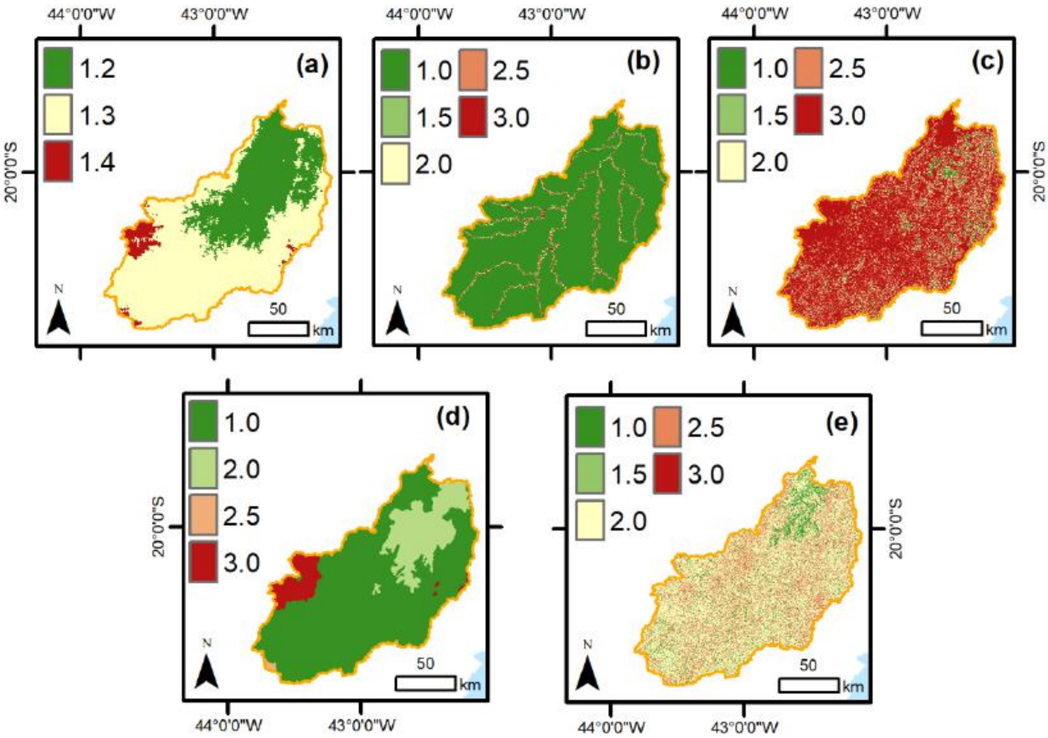

Figure 3. Criteria classification ranging from 1 to 3: (a) Precipitation (mm/monthly); (b) Proximity to drainage network (m); (c) Proximity to forest patches (m); (d) Soil class; (e) Slope (º).

Table 3. Pairwise matrix for the Rio Doce Basin – DO1. CR=0.043. A=Precipitation (mm/monthly); B= Proximity to drainage network (m); C= Proximity to forest patches (m); D= Soil class; E=Slope.

	A	**B**	**C**	**D**	**E**	**Vector V**	**Weight**
A	1	1/9	1/5	1/7	1/5	0.23	0.03
B	7	1	3	7	5	3.74	0.52
C	5	1/3	1	3	3	1.72	0.24
D	5	1/7	1/3	1	1	0.75	0.10
E	5	1/5	1/3	1	1	0.80	0.11
Total	23.00	1.79	4.87	12.14	10.20		

The resultant priority map (**Figure 4**), indicated 1.73% of Rio Doce Basin – DO1 with very high priority (6) for forest recovery; 5.18% with high priority (5); 57.88% with medium priority (4); 1.34% with low (3) and; 0.00% with very low priority (2). The restricted areas (1) represented 33.88% of the study area. We can assume that the solution is in accordance with the criteria and weights, considering that places classified as the highest priority were mainly those near to drainage network (**Figure 4a**). From the total area of DO1, 65% presented from medium to very high recovery priority, revealing that the entire area is highly degraded. Detailing the information in the permanent preservation areas across the river, 31.60% of the area is in a very high priority area, 26.31% with high, 21.05 with medium and 15.80% with low priority. The restricted area was 5.26% (**Figure 4b**).

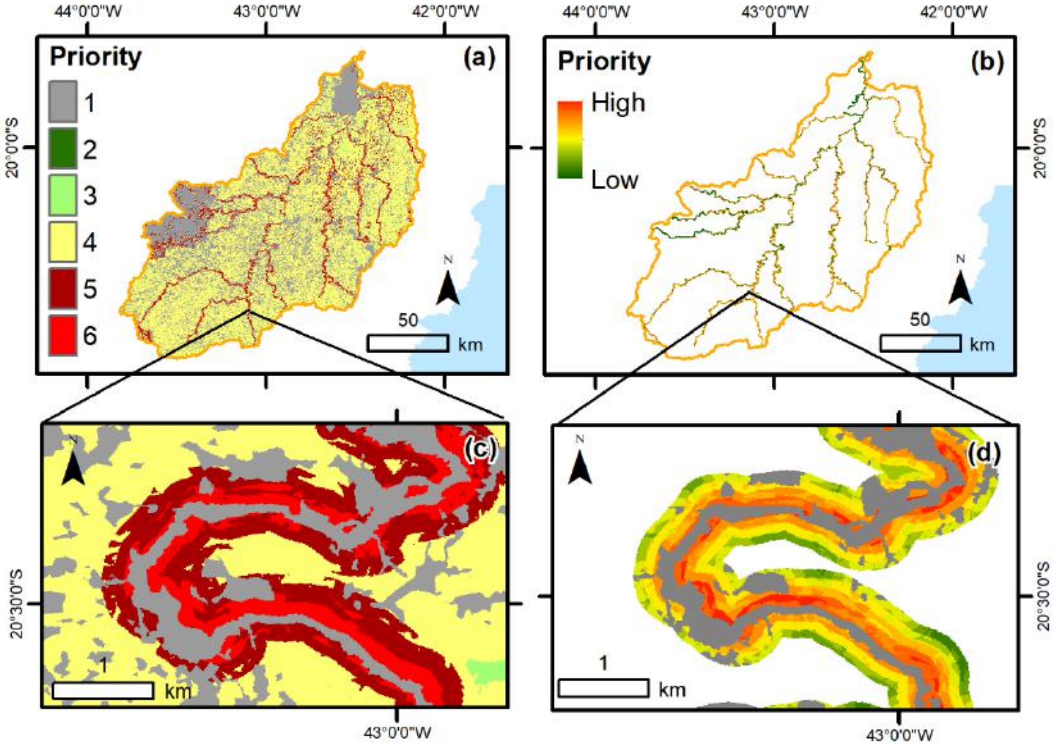

Figure 4. (a) Priority areas for forest restoration, (b) detailing the permanent preservation areas: (1) Restricted areas; (2) Very low; (3) Low; (4) Medium; (5) High and (6) Very high.

The method presented here may potentially be replicated, mainly in areas that play an important role in the global climate system, such as the Pantanal biome (Bacani et al. 2016). The Pantanal is one of the world's most biodiverse ecosystems and it is declared as a Biosphere Reserve and a World's Heritage Site (Schwerdtfeger et al. 2016), presenting an inundated area of approximately 150,000 km² (Gonçalves et al. 2011), providing an extraordinary flora and fauna. However, the dynamic of land use/land cover in Pantanal biome change is marked by deforestation for pasture expansion, resulting in a real threat to the ecological stability. Thus, accurate monitoring and understanding of changes are of significant importance to both the scientific community and local governments (Han 2015), that can be achieved by using MCDA and GIS analysis. In fact, these tools can be applied for all kinds of impacts, can be made site-time-specific or not, and quantitatively as well as qualitatively (Finnveden et al. 2003).

5. Conclusions

We used MCDA combined with GIS analysis to define priority areas for forest restoration in the Rio Doce – DO1 Basin. The criteria we used to select priority areas for forest restoration were precipitation, proximity to drainage network, proximity to forest patches, soil class and slope.

Our priority map indicated that from the total area of DO1, 65% presented a medium to very high recovery priority, revealing that the entire area is highly degraded. The method presented here may potentially be replicated throughout the whole Rio Doce Basin, as well as in other regions that require support for decision making in environmental planning, such as the Pantanal biome, marked by deforestation for pasture expansion.

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