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MODELING ECOSYSTEM SERVICES RELATED TO SOIL CONSERVATION IN THE CÓRREGO DANTAS WATERSHED, MUNICIPALITY OF NOVA FRIBURGO - RJ

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Resumo

Modelagem de serviços ecossistêmicos relacionados à conservação do solo na bacia hidrográfica do córrego dantas, Nova Friburgo – RJ. Este estudo utilizou o módulo para estimativa da perda de solo (*Sediment Delivery Ratio)* do modelo *Integrated Valuation of Ecosystem Services and Tradeoffs*, com o objetivo de avaliar os serviços ecossistêmicos relacionados à conservação do solo na bacia Córrego Dantas, localizada em Nova Friburgo – RJ, região com ocorrência de desastres causados por eventos extremos de precipitação. Foram analisados três cenários de uso e cobertura do solo, com foco na restauração florestal e na redução da exportação de sedimentos e perda de solo. O cenário baseado nas áreas prioritárias definidas em publicação referência para aplicação do estudo, produzido pelo Instituto Estadual do Ambiente, apresentou maior eficiência na redução da perda de solo. Os resultados indicaram que a presença da cobertura florestal, isoladamente, não seria suficiente para mitigar os processos erosivos, sendo necessário considerar fatores como declividade, tipo de solo e conectividade hidrológica. Nesse sentido, a localização das áreas de intervenção visando restauração florestal desempenha um papel crucial na eficiência dos projetos em alcançar os objetivos funcionais da paisagem, sendo este um fator considerado determinante no potencial da vegetação florestal para a redução do risco de erosão e na prestação de serviços ecossistêmicos. Este trabalho destaca a relevância da modelagem ecológica, e de ferramentas de acesso livre, para subsidiar a tomada de decisão em gestão territorial sustentável e conservação ambiental.
Palavras-chave: InVEST, erosão, restauração florestal.

Abstract

This study applied the Sediment Delivery Ratio module of the Integrated Valuation of Ecosystem Services and Tradeoffs model to assess ecosystem services related to soil conservation in the Córrego Dantas watershed, located in Nova Friburgo – RJ, a region prone to disasters caused by extreme precipitation events. Three land use and land cover scenarios were analyzed, focusing on afforestation and the reduction of sediment exports and soil loss. The scenario based on priority areas defined in a reference publication by the State Environmental Institute (Instituto Estadual do Ambiente) demonstrated the highest efficiency in reducing soil loss. While forest cover plays a role in erosion control, our results suggest that its presence alone is a limited factor, emphasizing the importance of incorporating slope, soil type, and hydrological connectivity into mitigation strategies. In this regard, the location of intervention areas for afforestation plays a crucial role in the efficiency of projects to achieve the functional objectives of the landscape, a factor considered determinant in the potential of forest cover to reduce erosion risk and provide ecosystem services. This work highlights the relevance of ecological modeling, and freely available tools, to support decision-making in sustainable territorial management and environmental conservation.
Keywords: InVEST, erosion, afforestation.

INTRODUCTION

Land use and land cover changes, overexploitation of natural resources, pollution, and climate change are significantly impacting the provision of hydrological ecosystem services (LOUMAN *et al.*, 2009). Rivers are becoming sediment repositories, compromising their ecological functions, affecting water quality and water supply availability (SALOMÃO *et al.*, 2020). This excessive accumulation of sediment in rivers is related to soil erosion, which intensifies the transport of particles to water bodies, altering their natural dynamics (OLIVEIRA *et al.*, 2023).

The soil loss process is considered as a global problem (WANG *et al.*, 2016;) and is intensifying in Brazil due to changes in land use and land cover and soil exploitation (OLIVEIRA; FEHR, 2020). Water erosion is the primary driver of soil degradation reducing its productivity (TOLEDO, 2023). This phenomenon is largely due to inadequate soil management, which facilitates particle transport through surface runoff (FREITAS *et al.*, 2021). The behavior of surface runoff is influenced by various terrain characteristics that impact erosion and its intensity, such as slope, vegetation cover, runoff pathways, soil type, infiltration capacity, and surface roughness (FREITAS *et al.*, 2021). Forest covered areas generally exhibit more stable soil characteristics, which reduce surface runoff and soil loss (SILVA *et al.*, 2015). On the other hand, exposed soils are directly impacted by precipitation, thereby increasing erosion (SOUSA; PAULA, 2019).

Understanding susceptibility to erosive processes enables the informed design of soil and water conservation structures and enhances the predictability of environmental impacts (XAVIER *et al.*, 2019). In this context, ecological modeling emerges as a powerful method for conceptualizing, quantifying, mapping, and monitoring ecosystem services across a landscape. It has been widely used to assess the impacts of different land use and land cover and management practices on hydrological processes (GOLMOHAMMADI *et al.*, 2014). These tools enable managers to project future landscape and ecosystem scenarios with the aim of restoring, conserving, or optimizing ecosystem services (DENNEDY-FRANK *et al.*, 2016). Ecological models enable the quantification of the benefits provided by natural structures, such as sediment retention and the consequent reduction in reservoir sedimentation (CARVALHO-SANTOS; HONRADO; HEIN, 2014).

The Sediment Delivery Ratio (SDR) module from Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST®) model, is particularly notable for its accessible and intuitive approach, making it widely adopted both in academic studies and in environmental management practices (DENNEDY-FRANK *et al.*, 2016; FERREIRA; RODRIGUES, 2024). The objective of this tool is to map sediment generation and its delivery to streams, assess ecosystem services provided by green infrastructures, and support natural resource management decisions (NATURAL CAPITAL PROJECT, 2023). According to Koo, Kleemann, and Furst (2018), effective land use and land cover management strategies require tools that assess different land use scenarios and the impacts of human interventions on ecosystems and ecosystem service provision. Ougougdal *et al.* (2020) demonstrated that the InVEST SDR model empowers managers to implement soil conservation measures and water management plans that are specifically tailored to the region's unique characteristics. Marques *et al.* (2021) emphasized the importance and applicability of this model in estimating soil loss potential at regional and national scales.

This paper aims to contribute to water security decision-making in the mountainous region of Rio de Janeiro State by analyzing the provision of ecosystem services associated with soil conservation across various land use and land cover scenarios. The Córrego Dantas watershed, located in Nova Friburgo – a region with a history of hydrological disasters – was chosen as the study area, with a specific focus on priority areas for afforestation and the reduction of sediment export.

MATERIALS AND METHODS

Area of Interest

Located in the mountainous region of Rio de Janeiro State, specifically within Nova Friburgo, the Córrego Dantas River watershed is characterized by mountain chains and steep terrain, with altitudes ranging from 900 m to 1300 m. Notably, this watershed was the most affected area during the 2011 mega-disaster occurred of Nova Friburgo, which experienced high incidences of landslides (NUNES; FREITAS, 2018).

The watershed (Figure 1) was delineated using digital elevation model (DEM) of the terrain with a resolution of 12.5 m, from the year 2011, provided by ALOS (The Advanced Land Observing Satellite) and PALSAR (The Phased Array L-band SAR) instrument, launched in January 2006 by the Japan Aerospace Exploration Agency (JAXA). The Córrego Dantas watershed, covering approximately 53 km², is adjacent to the Bengalas River watershed in the center of Nova Friburgo, characterized by urban expansion area.

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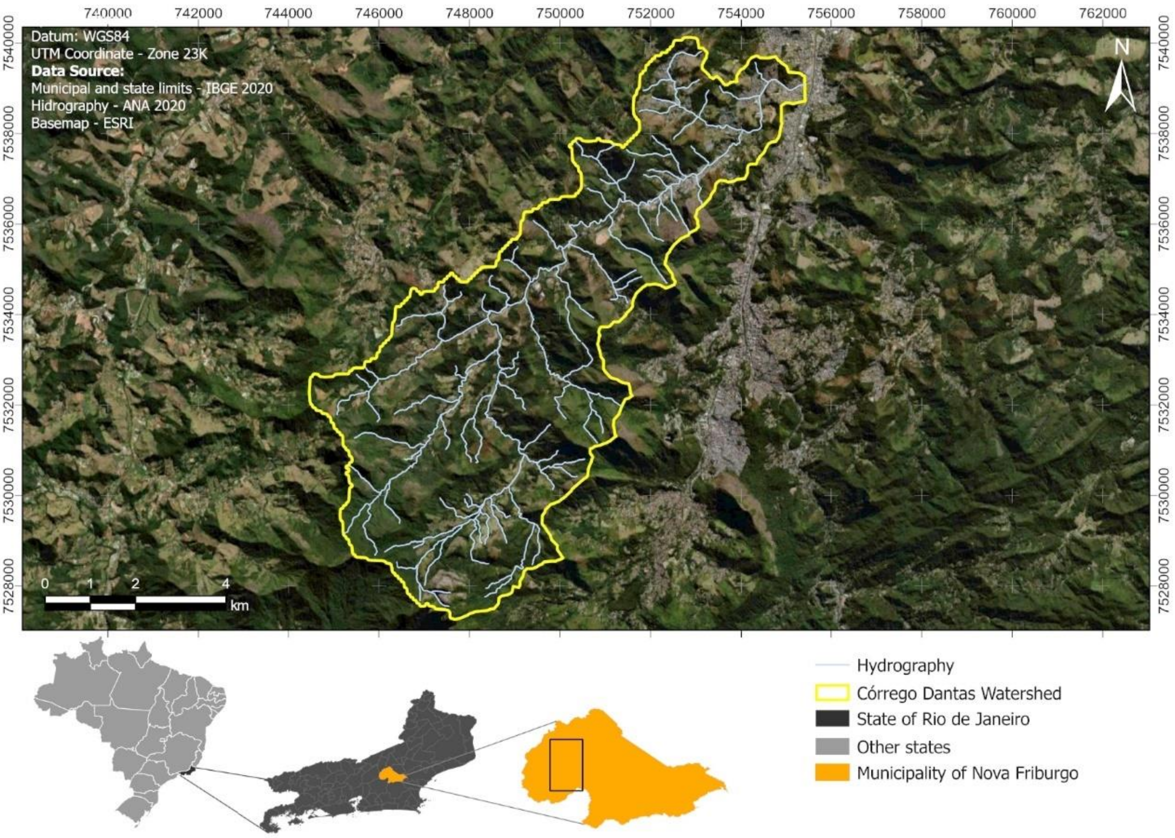

Figure 1. Córrego Dantas watershed location map, Nova Friburgo - Rio de Janeiro.
Figura 1. Mapa de Localização da bacia hidrográfica Córrego Dantas, Nova Friburgo - Rio de Janeiro.

Modeling Sediment Production

The InVEST SDR model estimates the annual soil loss for each pixel (pixel i), in tons per hectare per year, using the Universal Soil Loss Equation (USLE).

$$USLE_i = R_i \times K_i \times LS_i \times C_i \times P_i$$

Where: $USLE_i$ corresponds to the soil loss for pixel i (t/ha/year), R_i is rainfall erosivity index for pixel i (MJ.mm/ha.hr), K_i represents soil erodibility for pixel i (ton.ha.hr/MJ.ha.mm), LS_i is slope length and steepness factor for pixel i, C_i corresponds to the land cover factor for pixel i, and P_i is the conservation practice factor for pixel i.

The model estimates sediment export by calculating the total amount of sediment reaching the stream from each pixel. Soil loss for each pixel varies according to the upslope contributing area and the downslope flow path (NATURAL CAPITAL PROJECT, 2023). The data required for SDR modeling are presented in Table 1.

Table 1. Database inputs for SDR InVEST model.
Tabela 1. Dados de entrada para o modelo SDR InVEST.

Description	Raster (resolution)	Data source
Watershed Boundaries	12.5 m	Alos Palsar (2011)
Digital Elevation Model	12.5 m	Alos Palsar (2011)
Rainfall Erosivity Index	1 km	GloREDa (ESDAC)
Soil Erodibility Index	250 m	GODOI *et al.* (2020)
Land Use and Land Cover Map	30 m	MapBiomas (2020)

The InVEST model operates according to the resolution of DEM raster, with 12.5 m resolution, assigning to each pixel the annual soil loss amount and the sediment delivery ratio to the river. Rainfall Erosivity Index (Factor R) used the raster obtained from Global Rainfall Erosivity Database (GloREDa), which is based on the European-scale Rainfall Erosivity Database (REDES). The global rainfall erosivity map provides a comprehensive dataset derived from 3,625 rainfall stations and approximately 60,000 years of rainfall records. The temporal coverage ranges from 30 to 40 years, predominantly from the last decade of 2000 to 2010, with a spatial resolution of 1 km and results expressed in MJ.mm/ha.h.year (PANAGOS *et al.*, 2023). The Soil Erodibility Index (Factor K) dataset was provided by Godoi *et al.* (2020), with 250m pixel resolution. The Factor K is estimated through the algebraic solution of the USLE nomograph (ton.ha.hr/MJ.ha.mm). Land use and land cover maps were obtained from Collection 6 of MapBiomas repository, considering the 2020 year (PROJETO MAPBIOMAS, 2020).

Biophysical parameters table (Table 2) was prepared using land use and land cover management values (Factor C) based on data collected by Costa *et al.* (2009). Regarding the parameter for soil management and use practices, value 1 was adopted, assuming the absence of such practices, in the scenario simulation.

Table 2. Biophysical table used by InVEST
Tabela 2. Tabela biofísica utilizada pelo InVEST

Code	Description	USLE C	USLE P
3	Forest	0.0001	1
9	Planted Forest	0.0085	1
15	Pasture	0.255882	1
21	Mosaic of Agriculture and Pasture	0.255882	1
24	Urban Infrastructure	0.0075	1
25	Other Non-Vegetated Areas	0.0075	1
33	Water	0	1

Legend: USLE C, soil cover management factor (dimensionless); USLE P, soil management and conservation practice factor (dimensionless).

The two calibration parameters (K and IC0), which determine the shape of the relationship between hydrological connectivity and the sediment delivery ratio, were assigned to the model's default values of 2 and 0.5, respectively. Similarly, the maximum sedimentation parameter was set to the default value of 0.8 (NATURAL CAPITAL PROJECT, 2023).

Scenarios definition

To assess the impact of different land use strategies on sediment export, three scenarios were defined based on existing environmental zoning and land use policies. The baseline scenario considered the land use in 2020 (Figure 2). The simulated scenarios had incorporated data from the state environmental agency, Instituto Estadual do Ambiente (INEA, 2019) of Rio de Janeiro, and the Nova Friburgo Zone Plan (MUNICÍPIO DE NOVA FRIBURGO, 2019).

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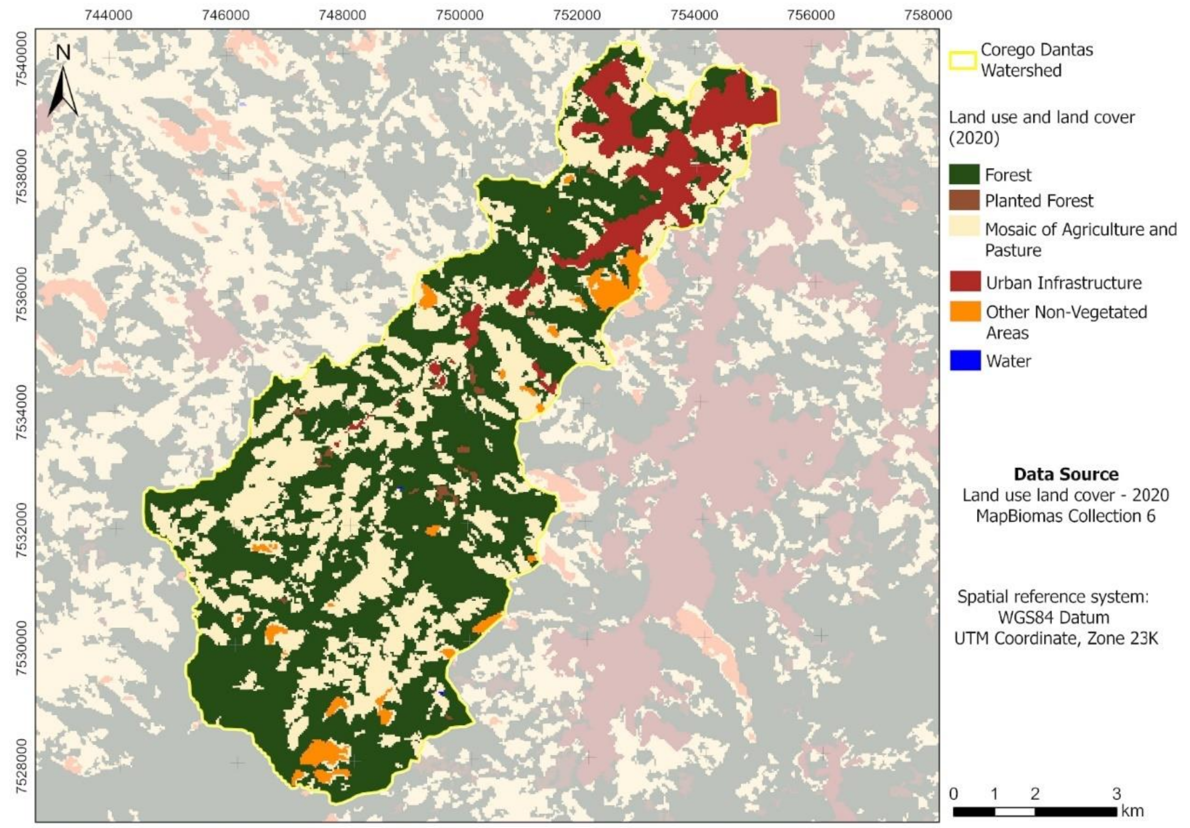

Figure 2. Land use and land cover map (2020).
Figura 2. Mapa de uso e cobertura do solo (2020).

The Priority Areas for Afforestation (INEA, 2019) were the criteria of Scenario 1 (C1) (Figure 3.a). The selected areas overlapped with erosive features and rocky cliffs identified in the Susceptibility Maps to Mass Gravitational Movements and Flooding of Rio de Janeiro, developed by Mineral Resources Research Company (CPRM) in 2015 (INEA, 2019).

Thus, in the proposed scenario C1, pasture and agricultural areas located within the priority areas for afforestation were identified in the Córrego Dantas watershed. Subsequently, a new land use and land cover map was generated, considering the forest cover in these classes.

Scenario 2 (C2) and Scenario 3 (C3) based on Nova Friburgo Zoning Plan (Figure 3.b) (MUNICÍPIO DE NOVA FRIBURGO, 2019), considered the entire area within the Urban Environment Macrozone, which represented the current urban areas and areas most suitable for expansion.

In addition, for scenario C3, the Natural Environment Macrozone, which includes areas designated for recovery and environmental conservation, the entire area within the Natural Environment Macrozone was simulated as forest cover.

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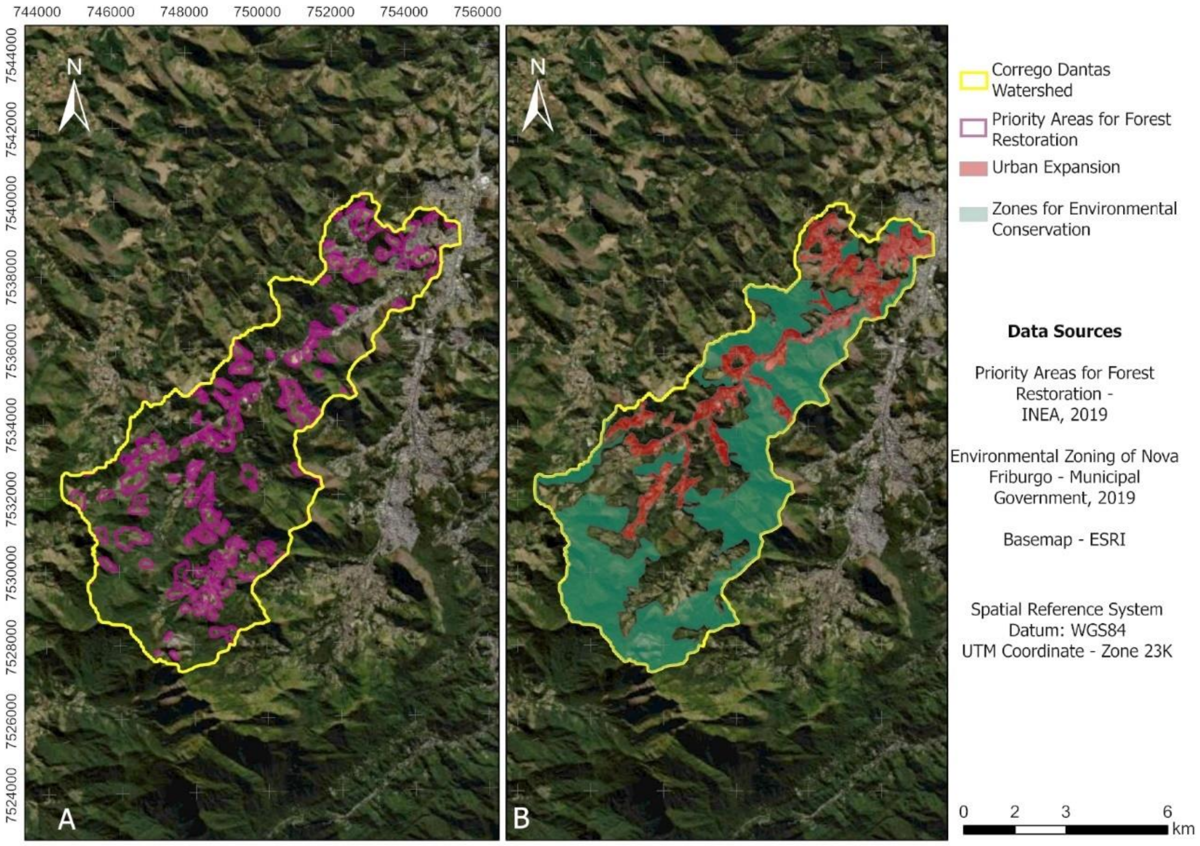

Figure 3. A - Priority Areas for Afforestation in the Córrego Dantas watershed. B - Urban and Environmental Conservation Macrozone
Figura 3. A - Áreas Prioritárias para a Restauração Florestal na bacia do Córrego Dantas. B - Macrozona Urbana e de Conservação Ambiental.

The land use and land cover scenarios elaborated for modeling SDR InVEST are presented in Table 3.

Table 3. Land use and land cover scenarios for SDR InVEST Simulation.
Tabela 3. Cenários de uso e cobertura do solo para simulação no SDR InVEST.

Scenarios	Land Use and Land Cover
Baseline	Land use and land cover for 2020 (MAPBIOMAS PROJECT)
C1	Priority Areas for afforestation in Nova Friburgo (INEA, 2019). Transition of pasture and agricultural areas into forest cover.
C2	Urban Environment Macrozone (MUNICÍPIO DE NOVA FRIBURGO, 2019). Transition of these areas into urban infrastructure.
C3	Natural Environment Macrozone (MUNICÍPIO DE NOVA FRIBURGO, 2019). Transition of these areas into forest cover.

Legend: Baseline – Land use and land cover 2020. C1 – Mosaic of Agriculture and Pasture in Priority Areas for Afforestation, converted to Forest. C2 – Urban Macrozone fully converted to Urban Infrastructure. C3 – Environmental Macrozone converted to Forest.

RESULTS

In the baseline scenario, forest cover in the year 2020 represented 56.67% of the watershed area. In Scenario 1, forest cover increased by approximately 12,96%, while in Scenario 3, it increased by 11,91%, and a reduction in pasture areas compared to the baseline scenario.

Table 4 presents the land use and land cover for each scenario.

Table 4. Land use and land cover MapBiomas classes, for each simulation scenario.
Tabela 4. Classs de uso e cobertura do solo do MapBiomas, para cada cenário de simulação.

Area (%) of land use and land cover classes				
Class	**Baseline**	**C1**	**C2**	**C3**
Forest	56.67	69.63	53.15	68.58
Planted Forest	0.47	0.47	0.45	0.43
Pasture	32.17	19.20	25.70	23.30
Mosaic of Agriculture and Pasture	7.90	7.90	17.96	7.68
Urban Infrastructure	2.79	2.79	2.73	0.00
Other Non-Vegetated Areas	0.01	0.01	0.01	0.01

Legend: Baseline – Land use and land cover 2020. C1 – Mosaic of Agriculture and Pasture in Priority Areas for Afforestation, converted to Forest. C2 – Urban Macrozone fully converted to Urban Infrastructure. C3 – Environmental Macrozone converted to Forest.

The soil loss, estimated by the model in tons per hectare per year, is presented in Figure 4, along with the variation in forest cover for each scenario.

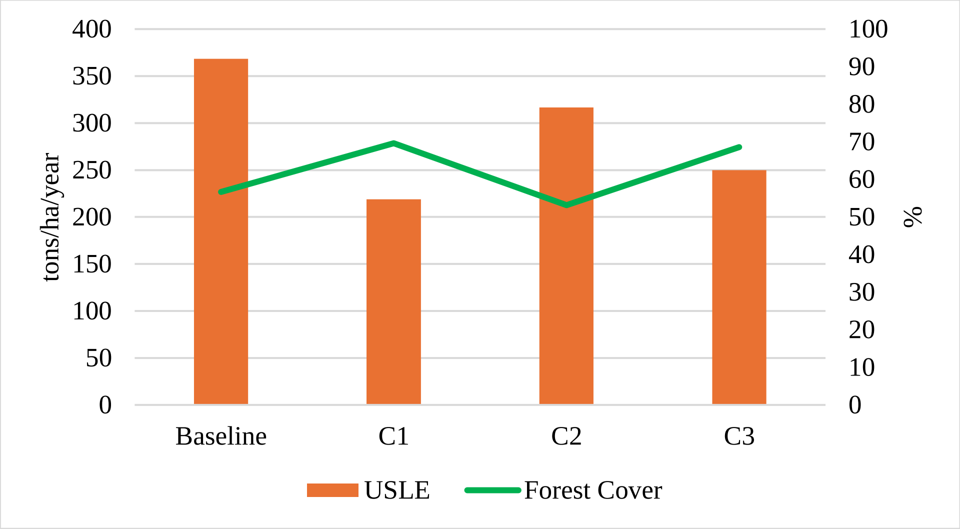

Figure 4. Percentage forest cover and soil loss data (USLE) for the Córrego Dantas watershed.
Figura 4. Porcentagem de cobertura florestal e dados de perda de solo (USLE) para a bacia hidrográfica Córrego Dantas.

As shown in Figure 4, scenario C1 resulted in a soil loss reduction of 41%, whereas C3 achieved a reduction of 32%. When comparing the scenarios, the results indicate that the scenario proposed by INEA (C1) showed the greatest reduction in soil loss. Despite the larger total forest area in C3, soil loss reduction was lower than C1, indicating that afforestation location is more critical than total forest expansion. This suggests a more effective allocation of priority areas for conservation and restoration aimed at mitigating soil degradation. This can be attributed to the fact that Scenario C1 prioritized areas with higher erosion susceptibility, whereas Scenario C3 considered a broader, but less targeted, forest expansion.

DISCUSSION

According to the results, it is noteworthy that the reduction of erosive processes is not solely related to forest cover; other factors must be considered when selecting relevant areas for afforestation. Although forest cover contributes to soil loss reduction, its effectiveness depends largely on strategic site selection. Lopes and Pinheiro (2013) emphasize that hydrological connectivity plays an essential role in sediment transport processes, influenced by factors such as land use, slope, and topographic characteristics. Their findings revealed that areas with greater hydrological connectivity exhibit enhanced sediment transport, whereas dense vegetation impedes connectivity and facilitates sediment retention by acting as a physical barrier. Forest cover expansion is not enough; factors such as slope, soil infiltration, and hydrological connectivity must be considered to enhance sediment retention. Regions with steeper slopes are more susceptible to accelerated surface runoff, soils with low infiltration capacity intensify water flow and erosion (COGO *et al.*, 2003).

The proposed scenarios highlight that afforestation planning is more effective when these factors are considered. C1 prioritized areas with high erosion risk, reduced soil loss by 41%; C3 increased forest cover, and resulted in 32% reduction, reinforcing the importance of targeted restoration efforts. This suggests that priority areas of C1 exhibited steeper slopes and higher soil erosion susceptibility, making them more responsive to restoration interventions, compared to the broader conservation zones in C3.

Forest allocation strategically is essential to optimizing the provision of ecosystem services. Thus, restoration plans must consider not only forest cover but also factors such as slope, soil types, and runoff pathways to maximize benefits. For instance, Ougougdal *et al.* (2020) emphasized that the effectiveness of forests in sediment retention depends on their location concerning topography and hydrological connectivity. Additional studies, such as those by Wang *et al.* (2016), also point out that land use and cover, together with topographic changes, are determinants in the intensification of erosive processes. Similarly, Marques *et al.* (2021) demonstrated that soil loss could be significantly reduced when forests are strategically positioned in more vulnerable areas. Furthermore, Carvalho *et al.* (2022) highlighted that vegetation in high-slope areas significantly reduces sediment transport to watercourses. These findings align with previous studies and reinforce that successful restoration strategies must integrate land use planning with topographic and hydrological assessments to maximize ecosystem service provision.

CONCLUSION

- Priority areas for afforestation defined by the state environmental agency will contribute to reducing soil loss in the watershed.
- Scenarios based on the Nova Friburgo Zone Plan classes exhibited lower efficiency compared to the scenario proposed by the state environmental agency.
- Results highlight the importance of an integrated and strategic approach to afforestation, where factors such as topography, hydrology, and soil types must be considered.
- The effectiveness and functionality of afforestation efforts, particularly in reducing erosion risk and providing ecosystem services, are largely determined by the spatial allocation of these areas.
- Detailed landscape analysis enables the selection of appropriate afforestation areas, ensuring that interventions are strategically located to maximize environmental benefits.

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