Revista Brasileira de Geografia Física v.18, n.02 (2025) 1028-1041.

Revista Brasileira de Geografia Física

ISSN:1984-2295

Homepage: https://periodicos.ufpe.br/revistas/rbgfe

Environmental Modeling for Watershed-based Territorial Planning

Huezer Viganô Sperandio[1]*, Rafael Alvarenga Almeida[2], Danielle Piuzana Mucida[1], Eric Bastos Gorgens[1], Anthoinny Vittoria Dos Santos Silva[1], Hugo Roldi Guariz[3], Jussiara Dias dos Santos[1], Guilherme Ribeiro Aguiar[4], Maíse Soares de Moura[5], Daniel Brasil Ferreira Pinto[2]

[1] Postgraduate Program in Forest Science, Universidade Federal dos Vales do Jequitinhonha e Mucuri, UFVJM, Diamantina, MG, Brazil. huezer@gmail.com, danielle.piuzana@ufvjm.edu.br, eric.gorgens@ufvjm.edu.br, jussiara.dias@ufvjm.edu.br
[2] Postgraduate Program in Technology, Environment and Society - Instituto de Ciência, Engenharia e Tecnologia, Universidade Federal dos Vales do Jequitinhonha e Mucuri – UFVJM, Teofilo Otoni, MG, Brazil rafael.almeida@ufvjm.edu.br, daniel.brasil@ufvjm.edu.br
[3] Instituto Federal Baiano, IF Baiano, Guanambi, BA hugo.guariz@gmail.com
[4] Postgraduate in Forestry Engineering – Universidade Federal de Lavras, Lavras, MG, Brazil ribeiroguilherme620@gmail.com
[5] Universidade Federal de Minas Gerais - UFMG, Belo Horizonte, MG, 31270-901, Brazil. maisedemoura2013@gmail.com

Artigo recebido em 15/08/2024 e aceito em 05/12/2024

A B S T R A C T

Environmental modeling of watersheds is essential for sustainable planning and resource management. This study applied detailed environmental modeling in the Ribeirão Santana Watershed (BHRS), located within the Espinhaço Range Biosphere Reserve in Minas Gerais, Brazil, to identify and map areas of soil fragility and agricultural suitability . Two methodologies were combined: the Conservative Use Potential (PUC) and the Universal Soil Loss Equation (USLE). The PUC was assessed based on lithology, soil types, and slope, while USLE considered erosivity, erodibility, topography, land use, and conservation practices. Results indicated that 76% of the watershed has medium to high agricultural potential, and over 85% shows mild to moderate soil losses (below 10 t/ha/year). The southern portion, with low agricultural potential, is recommended for native vegetation conservation, while the central and northern areas, more exposed to anthropogenic pressures, show higher soil loss rates, highlighting the need for enhanced soil and environmental management practices. This integration of PUC and USLE allows for precise identification of regions with higher environmental fragility and agricultural potential, supporting decisions on suitable land use and targeted conservation measures throughout the watershed. Such an integrated approach provides a comprehensive framework for sustainable planning and management, which can improve land use practices and help protect ecologically sensitive areas.
Keywords: environmental zoning, USLE, landscape designer, sustainable production, decision tools

Modelagem Ambiental para Planejamento Territorial Baseado em Bacias Hidrográficas

R E S U M O

A modelagem ambiental de bacias hidrográficas é essencial para o planejamento sustentável e gestão de recursos naturais. Este estudo aplicou uma modelagem ambiental detalhada na Bacia Hidrográfica do Ribeirão Santana (BHRS), localizada na Reserva da Biosfera da Serra do Espinhaço, em Minas Gerais, Brasil, com o objetivo de identificar e mapear áreas de fragilidade do solo e de aptidão agricola. Foram combinadas duas metodologias: o Potencial de Uso Conservacionista (PUC) e a Equação Universal de Perda de Solo (USLE). O PUC foi avaliado com base na litologia, tipos de solo e declividade, enquanto a USLE considerou erosividade, erodibilidade, topografia, uso do solo e práticas de conservação. Os resultados indicaram que 76% da bacia possui potencial agrícola médio a alto, e mais de 85% apresenta perdas de solo leves a moderadas (abaixo de 10 t/ha/ano). A porção sul, com baixo potencial agrícola, é recomendada para conservação da vegetação nativa, enquanto as áreas central e norte, mais expostas a pressões antrópicas, apresentam taxas mais elevadas de perda de solo, ressaltando a necessidade de práticas aprimoradas de manejo conservacionista do solo e gestão ambiental. Essa integração das metodologias PUC e USLE permite a identificação precisa das regiões com maior fragilidade ambiental e potencial agrícola, apoiando decisões sobre o uso adequado da terra e medidas de conservação específicas em toda a bacia. A abordagem integrada oferece um quadro abrangente para o planejamento e gestão sustentável, que pode melhorar as práticas de uso da terra e ajudar na proteção de áreas ecologicamente sensíveis.
Palavras-chave: zoneamento ambiental, USLE, modelagem da paisagem, produção sustentável, ferramentas de decisão

Introduction

Agricultural productivity interferes directly with social stability and the supply of ecosystem services to the planet, especially in poorer regions (Panagos et al., 2019; Ahmad et al., 2020; Abera et al., 2020; Oberreich et al., 2024). Neglecting the specific natural fragility of each soil type, especially in situations induced by erosive processes, can lead to high levels of soil degradation, which in specific contexts may be irreversible or difficult to remedy (Moura et al., 2024). The United Nations (UN), through the Sustainable Development Goals (SDGs), identifies natural resources and soil as of crucial importance for sustainable development and food security (Viana et al., 2022).

Losses in the order of 847 million tons of soil per year are estimated for the Brazilian territory, resulting from the process of erosion in annual crops, causing direct costs of over US$ 1.65 billion (Pinto et al., 2022). Environmental processes are interconnected, and soil is directly linked to water resource quality, biodiversity, and human health (Cecone et al., 2018, Guerra et al., 2022).

Environmental planning is an effective way to manage and organize hydrographic basins, aiming at a sustainable environment. This makes it possible to understand the territory holistically, allowing a spatial understanding of the problems and organizing actions to minimize them (Cecone, et al., 2018; Costa et al., 2019; Zhou et al., 2022).

Comprehending the fragility of the area is crucial for establishment and development of human activities, especially when it comes to the use of land for raising livestock and agriculture. Quantitative methods provide parameters for planning land use and occupation, especially in watersheds (Rocha & Sparovek, 2021; Pereira & Cabral, 2021).

This is especially important when the area is recognized for its unique ecological, biological, and cultural values and for its role in promoting sustainable development. To identify such areas, UNESCO created a status of Biosphere Reserve. The first Biosphere Reserve was created in Spain, in the province of La Rioja. Since then, we have 759 Biosphere Reserves, representing diverse ecosystems, including forests, grasslands, deserts, wetlands, and coastal areas (UNESCO, 2024).

A Biosphere Reserve typically consists of three interrelated zones, including strictly protected areas, followed by restricted and transition zones. Those last zones allow some types of human activities to be managed sustainably. However, there is a need for more socio-environmental studies overlapping different techniques to assess land fragility and orient land use planning.

This study contributes by integrating two advanced environmental modeling methods. One evaluates agricultural suitability by crossing the lithology, the slope, and the soil type (Costa et al., 2017; Costa et al., 2019), and another estimates area fragility by means of soil erosion rate caused by rainfall and runoff (Alavínia et al., 2019). The innovation lies in applying combined modeling techniques for land vulnerability assessment in ecological reserve context.

It is hypothesized that the fragility of the area will reflect the current state of soil degradation due to land use practices and can serve to identify high erosion rates where interventions should be considered. Highlighting areas most vulnerable to soil degradation allows managers to target allocation of resources and efforts to mitigate erosion and maintain long-term agricultural productivity. This study aims to conduct detailed environmental modeling to identify and map agricultural suitability and the current soil fragility within a watershed.

Methods

The Ribeirão Santana watershed (BHRS) is in the municipality of Felício dos Santos, northeast of Minas Gerais (Figure 1), and has approximately 7,200 ha (Gorgens et al., 2021). According to the Köppen-Geiger classification, the climate regime in the region is altitude tropical (Cwb), characterized by mild, humid summers and cool, dry winters (Kottek et al., 2006). Precipitation rates vary from 1,250 mm to 1,550 mm, and the average annual temperature is 20º C (Alvares et al., 2014).

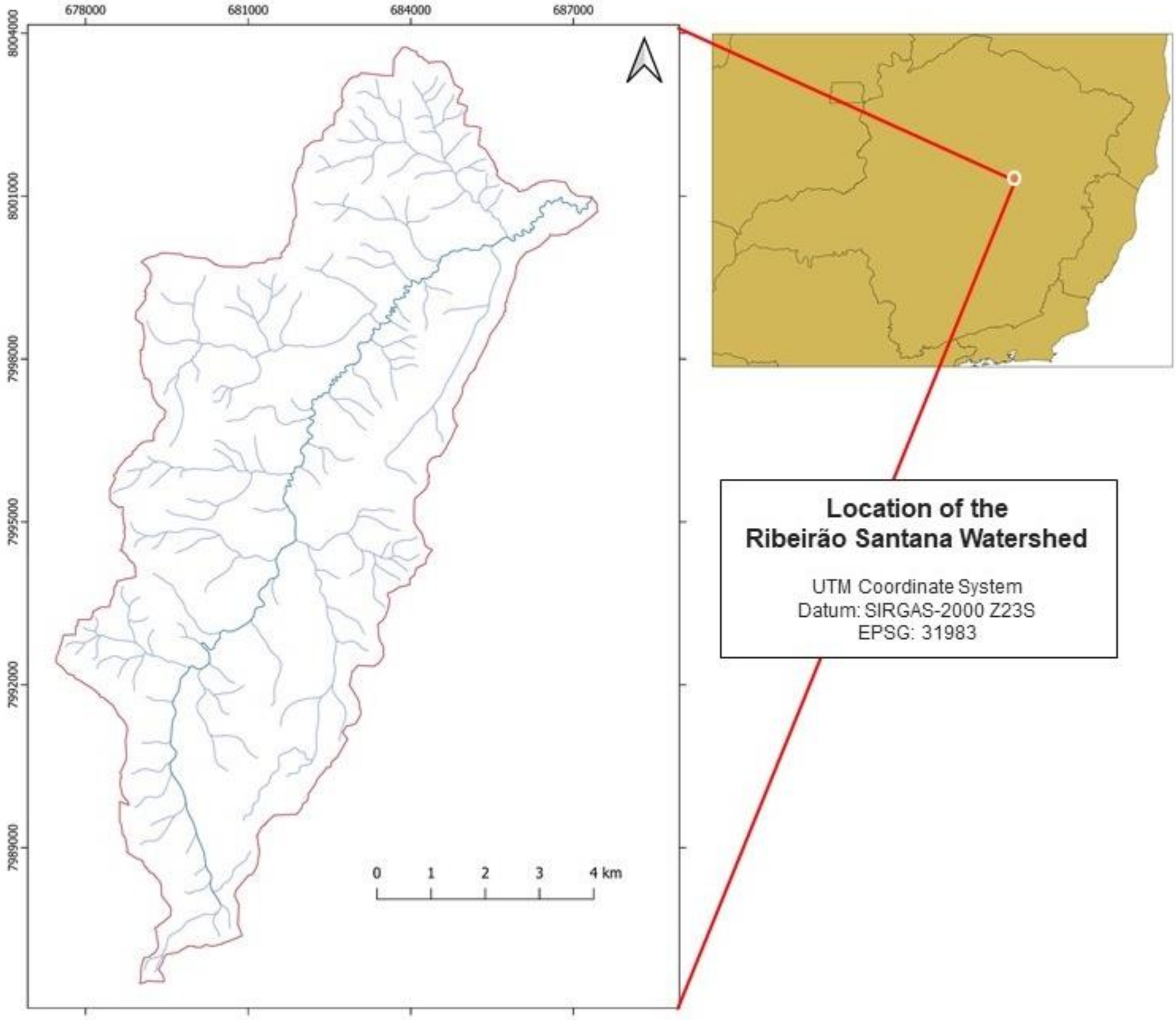

Figure 1: Delimitation and location of the Ribeirão Santana watershed.

The basin has a smooth to undulating relief in its low portion and undulating to mountainous in the high portion, as classified by EMBRAPA (1999). The elevation varies from 709 meters downstream to 1,826 meters at the head of the basin (Figure 2A). The basin is formed by three major geological domains: metamorphic rocks of sedimentary origin from the Espinhaço Supergroup (Diamantina Group) in the upper portion, metamorphic rocks of sedimentary origin from the São Francisco Supergroup (Macaubas Group) in the middle portion, and metamorphic rocks of igneous origin, of the Rio Itanguá Granitoid (Figure 2B).

According to the EMBRAPA/RADAM soil class map of Minas Gerais (1:1,000,000 scale, available at http://geoinfo.cnps.embrapa.br/layers/geonode %3Alev_mg_estado_solos_lat_long_wgs 84_vt) the soils in the basin are classified as Haplic Cambisol, Red-Yellow Argisol, Litholic Neosol and Red Latosol (Figure 2C).

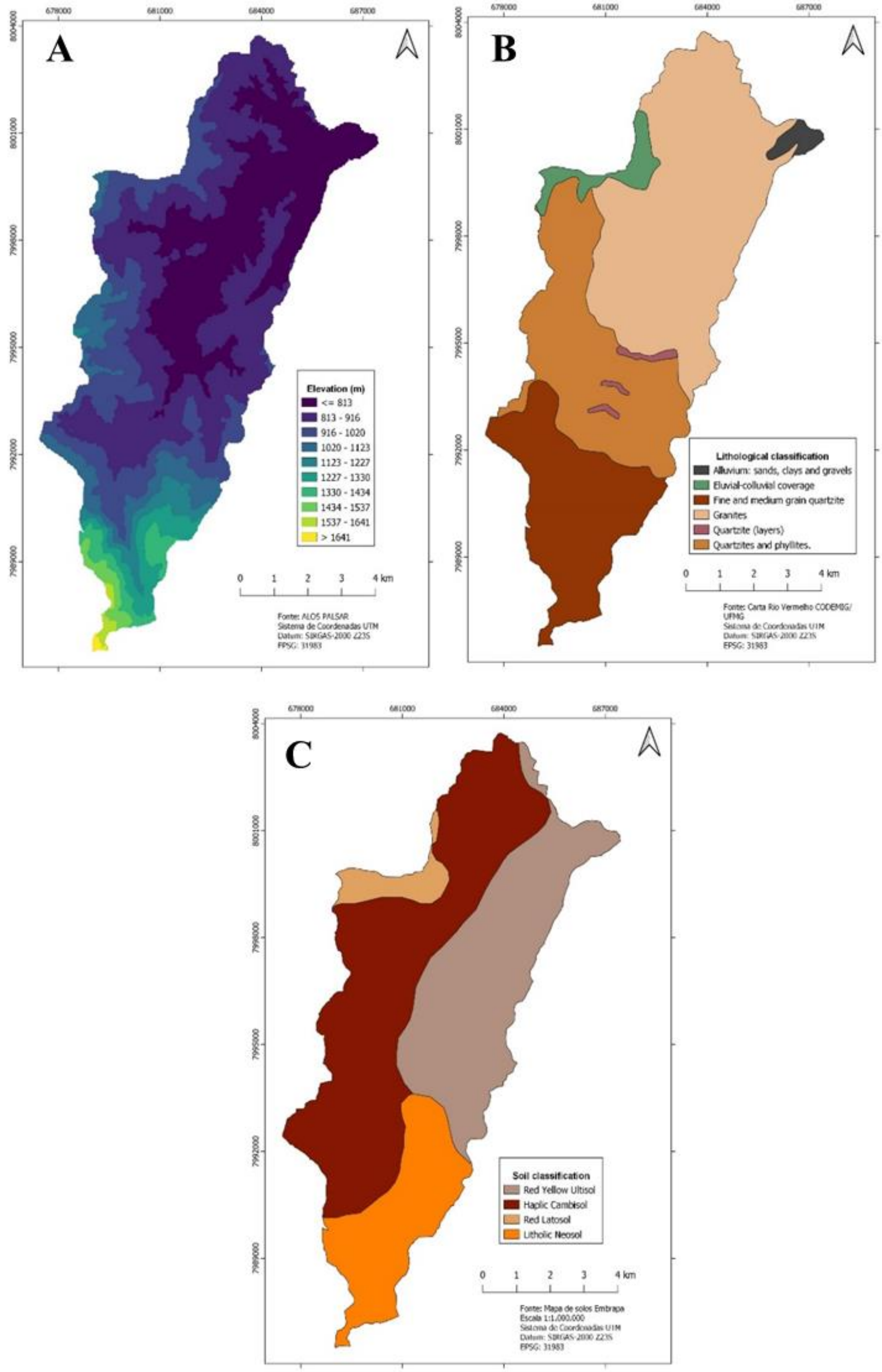

Figure 2: Digital Elevation Model (A), Geological Formations (B), and Soil Types (C) of the Ribeirão Santana Basin. Source: Gorgens et al. (2021).

The lithology classes were based on the geological map, on a scale of 1: 1,000,000 (available at http://www.portalgeologia.com.br/index.php/mapa/?lang=en). Soil classes were based on the EMBRAPA/RADAM soil map at a scale of 1:1,000,000, and the slope was calculated from the elevation obtained by the Shuttle Radar Topography Mission (SRTM) with a resolution of 1 arc second (approximately 30 m).

The slope was reclassified as flat (0 to 3% - potential 5), gentle undulating (3 to 8% - potential 4), moderately undulating to undulating (8 to 20% - potential 3), strong undulating (20 to 45% - potential 2) and hilly to steep (> 45 % - potential 1) (Costa et al., 2017).

To evaluate the potential for agriculture, the three layers were combined by weighting 50% of the slope map, 39% of the soil, and 11% of the lithology (Costa et al., 2017). The final value ranging from 1 to 5 expresses potential for agricultural use from a sustainable perspective.

We also computed the Universal Soil Loss Equation (USLE) map considering a soil loss model (t $ha^{-1}year^{-1}$) for a given location based on five main factors: rainfall erosivity index (R - MJ mm $ha^{-1}h^{-1}year^{-1}$), soil erodibility factor (K - t h MJ^{-1} mm^{-1}); topographic factor, which encompasses the length of the ramp and degree of declivity (LS - dimensionless), management (C - dimensionless), and conservation practices factor (P - dimensionless) (Pinto et al., 2020).

The erosivity factor (R) was obtained using an Artificial Neural Networks methodology (Rehman et al., 2024), which estimated erosivity values for the entire state of Minas Gerais. It refers to an intrinsic characteristic of the soil that represents its susceptibility to erosion, being linked to factors that affect the infiltration speed, permeability, total water storage capacity, and resistance to the action of rain (Lee et al., 2021). Each soil class found in the basin was associated to an erodibility (K) value defined as recommended by Godoi et al. (2021).

The slope of the terrain and the length of the slope influence water erosion. From the SRTM data, the hydrologically consistent digital elevation model (MDEHC), the LS-factor was computed according to Michalopoulou et al. (2022). The land use and occupation map were made using Sentinel 2 images (10 meters resolution), using the non-supervised k-means classification tool for four random centers. Subsequently, this classified image was transformed into a vector, and the areas were manually adjusted based on Google Earth images. The management (C) and conservation (P) factors were established for each land use and management class (Tesfaye et al., 2024).

Results

Potential for agricultural use

The agricultural potential score for the study area averaged 2.87 (on a scale between 1 – low, and 5 - high), ranging from 1.07 to 4.49 (Figure 3). It was found that 5.58% of the basin has very low suitability for agricultural use, 16.58% has low suitability and 57.73% of the basin has medium suitability for agricultural use. Areas with high and very high agricultural suitability correspond to 16.80% and 3.12% of the basin, respectively.

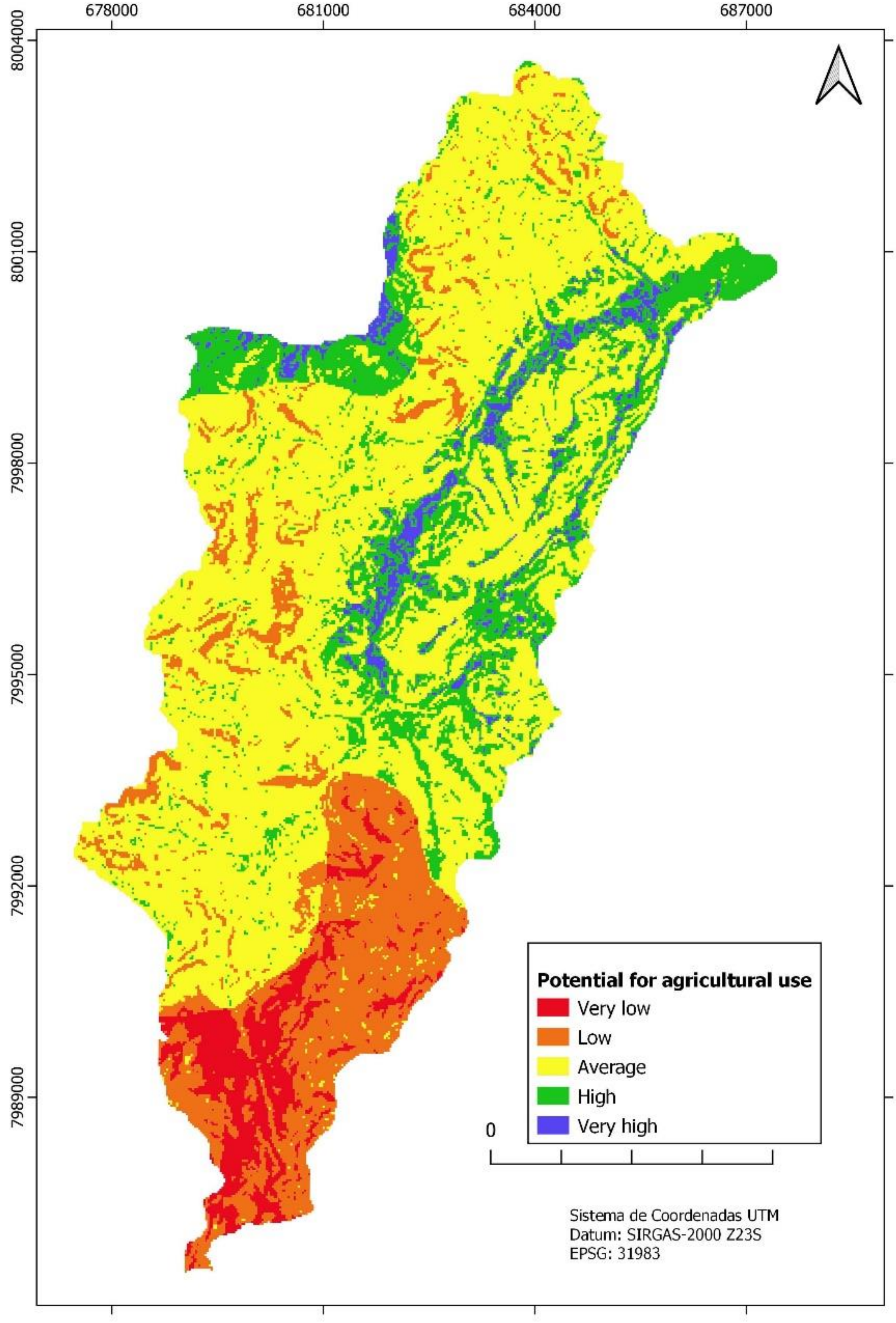

Figure 3: Agricultural suitability of the studied watershed.

Soil losses

The erosivity in the BHRS has a value of 3,862 MJ mm ha^{-1}h^{-1}year^{-1}, considered middle class (Godoi et al., 2021). For each soil of the basin, the erodibility was defined being for the Red Latosol (0.018 th MJ^{-1} mm^{-1}), Red Yellow Ultisol (0.047 th MJ^{-1} mm^{-1}) Haplic Cambisol (0.049 th MJ^{-1} mm^{-1}) and Litholic Neosol (0.036). Erodibility was classified according to Mannigel et al. (2002) as average for Latosol, very high for Ultisol and Cambisol, and high for litholic soils.

The topographic factor LS characterizes the flow velocity and indicates the risk of soil erosion in watersheds (Kebede et al., 2021). There was a variation from 0.03 to 45.87 in the topographic factor in the basin under study (Figure 4A).

The study area was categorized into nine land use and land cover classes (Figure 4B and Table 1) linked to natural and anthropic environments. After this categorization, the soil use and management factor for the BHRS was determined (Table 1). No soil conservation practices were evidenced in the basin area, so the conservation practices factor was used as a value of 1. The highest CP values are associated with land use classes with little or no land cover (exposed soil, Agriculture and Pasture) that most contribute to soil loss (Figure 5). The average soil loss in the basin is 4.29 Mg ha^{-1} year^{-1}. In 73.78% of the basin area, estimated losses of less than 5 Mg ha^{-1} year^{-1} occur, considered mild to moderate (Beskow et al., 2009; Thomas et al., 2018) (Table 2).

.

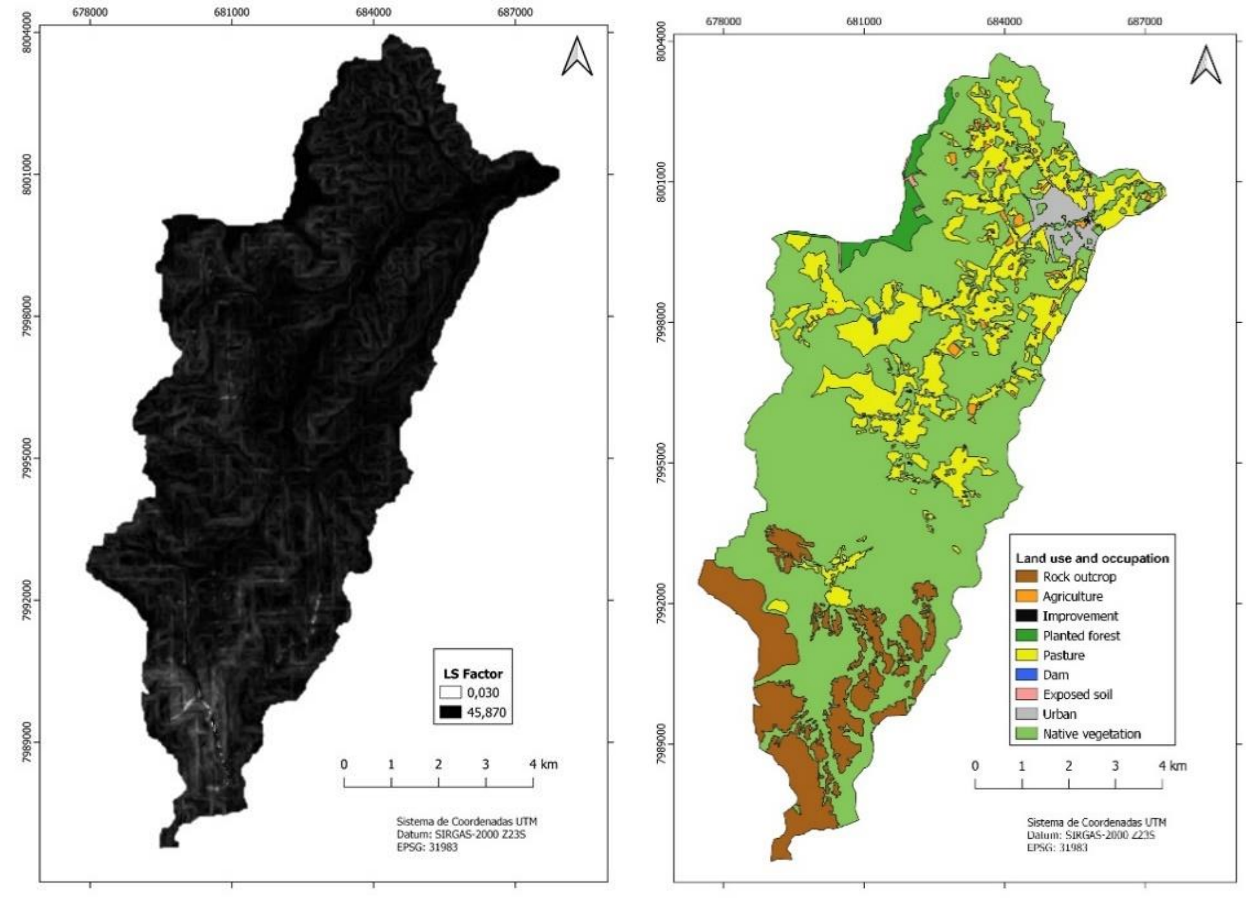

Figure 4: (A) Topographic factor of the Ribeirão Santana basin (B) Land use and occupation of the watershed.

Table 1: Classes of land use and occupation in the watershed: area and factor of conservation practices (CP)

Land Use and Occupancy	Percentage of area (%)	CP Factor*
Rock outcrop	11,81	0,00001
Native vegetation	64,64	0,042
Planted forest	1,66	0,0026
Improvement	0,06	0,00005
Exposed soil	0,21	1
Dam	0,05	0
Pasture	18,99	0,025
Urban	1,81	0,00005
Agriculture	0,76	0,1

*adapted from Pinto et al. (2021) and Tesfaye et al. (2024).

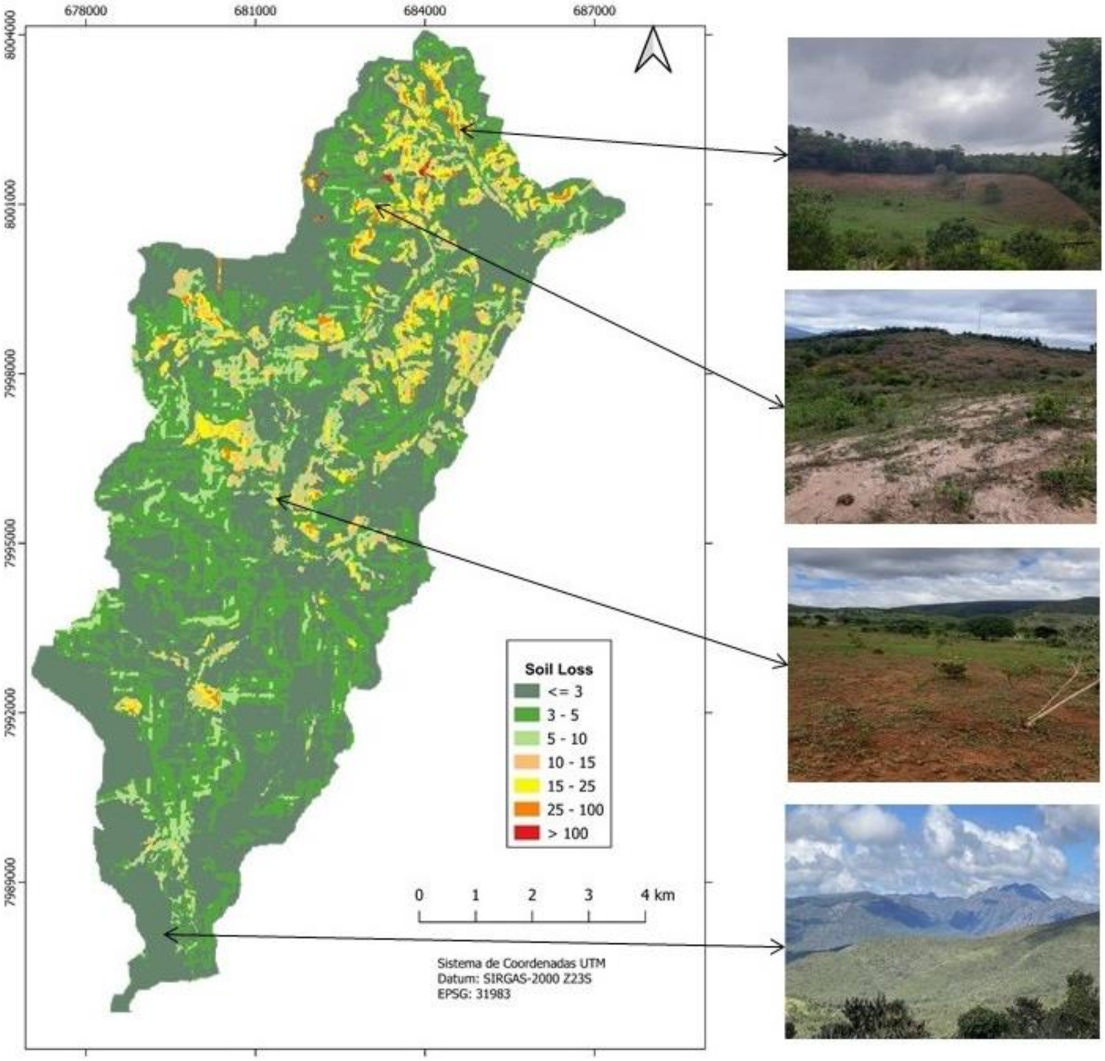

Figure 5: Spatialized estimates of soil losses and overview of some areas in the watershsed.

Table 2: Soil losses in the watershed

Soil loss values (t.ha ^{1}.year ^{1})	**Interpretation classes**	**% of the basin area**
0 – 2,5	Slight	49
2,5 - 5	Mild to moderate	24,78
5 - 10	Moderate	12,21
10 - 15	Moderate to high	6,65
15 - 25	High	4,88
25 - 100	Very high	1,78
> 100	Extremely high	0,70

Discussion

The watershed is partially inserted in the phyto-physiognomy of Campos Rupestres of Range Espinhaço. In 2005, the region was recognized by UNESCO as a Biosphere Reserve, and its extension was revised growing 220% in 2018 (Andrade et al., 2018). The Biosphere Reserve is a biodiversity hotspot, where approximately 40% of the species are endemic with varying degrees of rarity and conservation strategies of life (FBG, 2015; Morellato & Silveira, 2018; Guedes et al., 2020; Rapini et al., 2021).

The watershed, in addition to its environmental importance, is an essential source of water to supply the municipality of Felício dos Santos (MG) and contributes to Araçuaí river. The main water recharge in this region comes from numerous peatlands of Espinhaço Range (Silva et al., 2022). In this way, land use and occupation is fundamental to conserve biodiversity, edaphic and water resources, while support social development (Morandi et al., 2018; Scalco & Souza, 2019).

The agricultural suitability methodology (PUC) was developed to integrate geomorphological, pedological and geological criteria (Costa et al., 2017; Costa et al., 2019; Mucida et al., 2023, Costa et al., 2023; Moura et al., 2024). This approach makes it possible to synergistically identify areas with more outstanding potential for agroforestry uses, surface water recharge and natural resistance to erosion processes.

The southern portion of the watershed naturally has a low potential for agricultural use, mainly associated with Litholic Neosols and high slope. This area is occupied by native vegetation (the rocky fields of Serra do Espinhaço) and belongs to the buffer zone of the Rio Preto State Park. It is important to emphasize that areas identified as having low agricultural suitability may have other valuable benefits for human beings and should not be considered unimportant.

The antropogenic uses are concentrated in the central and northern part of the watershed, with the presence of pastures and agriculture. They are associated primarily with the presence of the lithological formation of the Itanguá Granitoid and the formation of well-developed and fertile soils. These areas present a high variation in potential for agricultural use and soil losses, associated mainly with the slope.

Erosivity, a direct parameter of the fragility model (USLE), is the driving force of rainfall to cause soil erosion. Raindrop impact and surface washing occur when infiltration capacity is exceeded (Panagos et al., 2022). Thus, the less structured the rain's soil will reach, the greater the drag efficiency. Although Erosivity is classified as average, it favors the variation of losses when associated with other vital factors of soil losses. For the entire Araçuaí River basin (in which this study area falls), a minimum value of 7,680 MJ mm $ha^{-1}h^{-1}Year^{-1}$ was found (Santos Neto & Christóforo, 2020).

Relief significantly influences both the fragility and the agricultural suitability results, being a determining factor in the current watershed (Beskow et al., 2009; Lense et al., 2020). The areas with high soil loss are dominated by steep slopes with poorly managed pasture or exposed soil. The LS factor presented significant variation (0.00 to 45.87) due to the characteristics of the relief in the basin, with higher values of the LS factor concentrated in the places of the greater declivity (Deng et al., 2021).

Many factors affect soil erosion, and the processes underlying its change are highly non-linear (Huang, 2018). Although different models to predict soil erosion are primarily associated with geographic information systems, it remains challenging to accurately quantify soil losses in each area. This fact is related to the precariousness of maps and detailed databases for each location (Godoi et al., 2021). It is recommended an effort to build better databases, to support modelling parameters of be adjusted and made more reliable.

In this work, by associating the agricultural suitability with area fragility (USLE), it was possible to carry out a detailed diagnosis of the land use in the watershed. The understanding provided by the PUC and USLE together makes it possible to balance economic opportunities, taking advantage of the productive potential of areas while assessing the risks associated with the use of areas with low potential (Costa et al., 2017; Costa et al., 2019; Moura et al., 2024). This integration allows for a more accurate and practical assessment of the viability of different land uses, promoting more sustainable and informed management of natural resources.

The watershed is occupied by small properties under family farming (Gorgens et al., 2021). In these areas, livestock raising, the main anthropic use of the land in the area, is conducted in an extensive system. When the grass is exhausted, the animals are moved out during a period. It is possible to verify partures with exposed soil and others with low production of dry matter. This fact puts pressure on the ecosystem since low financial returns from livestock activities result in area expansion to compensate for the loss. Consequently, soil erosion, river silting and loss of biodiversity increases (Michalk et al., 2019; Vasques et al., 2019; Freitas et al., 2020; Costa et al., 2024).

Even in the few areas occupied by agriculture, where the cultivation of annatto predominates, plantation management is carried out so that almost all the vegetation cover is removed, providing surface runoff and soil losses. Adopting conservation support practices, especially in areas with prolonged and/or steep slopes, is necessary to ensure adequate erosion control (Cunha et al., 2017; Pandey et al., 2021).

The high percentage of agricultural suitability (77.65% higher than 2.6) combined to the high percentage of moderate fragility in the watershed, reinforce the importance of counceling the local formers to adopting good agroforestry practices (Montagnini & del Fierro, 2024). In time and/or space, these systems associate species with robust root systems capable of penetrating denser layers and promoting soil restructuring with the main crop for soil restructuring and maintenance of favorable characteristics for agriculture (Ghimire et al., 2024).

One point to highlight is that although the role of rural producers in managing the landscape has been addressed in some works, it is only tangentially treated in studies that provide support for landscape management (Sherren et al., 2012; Meybeck et al., 2024;). To preserve the environment and its interrelations, which culminate in sustainability, ecosystem services, and the effectiveness of public policies, it is crucial to understand the values and motivations of rural producers (Montagnini & del Fierro, 2024; Zhang, 2024). It is important to note that while governments and corporations have decision-making power at the macro level, farmers make numerous decisions at the micro level (Sherren et al., 2012). Thus, it is essential to develop mechanisms that capture the understanding and perspectives of farmers since, with the intensification of production systems on a global scale, the individual decisions of agricultural landowners have a direct impact on the environmental conditions of watersheds (Zhang, 2024; Moura et al., 2024).

The integrated analysis of agricultural suitability (PUC) and area fragility (USLE) revealed important insights into the relationship between agricultural potential and land use. While agricultural suitability is static, with attributes that do not vary over time and indicate the appropriateness for agricultural use, area fragility is dynamic, reflecting changes resulting from current land use. This approach thus combines a static methodology with a dynamic one, allowing fragility analysis to serve as an indicator of management quality.

This integration makes it possible to assess whether areas with higher agricultural potential are being efficiently utilized. In the studied watershed, areas with medium agricultural potential often showed higher soil loss rates, highlighting the critical influence of management practices in mitigating these losses.

Conclusion

The use of the methodologies for mapping agricultural suitability and area fragility provided the spatialization and identification of significant weaknesses regions in the watershed, favoring the localized adoption of corrective and preservation actions.

The synergistic application of the Universal Soil Loss Equation (USLE) and the Agricultural Use Potential (PUC) methodologies enabled a comprehensive and nuanced diagnosis of the watershed's potential and current use patterns. This integrated approach provided valuable insights into the complex interplay between agricultural suitability and erosion vulnerability, facilitating a more robust analysis of land use dynamics and conservation needs within the basin.

Acknowledgments

Gratitude is extended to FAPEMIG (APQ-00943–21 and APQ-00185–2), CNPq (Training of Doctors in Strategic Areas 401053/2019-9 and Research Productivity 306386-2022-4), the Universidade Federal dos Vales do Jequitinhonha e Mucuri (UFVJM), and the Nucleus of Study and Research in Productive Environmental Zoning (NEPZAP-UFVJM). Partial funding for this study was provided by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

References

Ahmad, I., Dar, M. A., & Andualem, T. G. (2020). Assessment of soil loss rate-Lake Tana basin, Ethiopia. *Arab Journal of Geosciences*, 13(1), 15. https://doi.org/10.1007/s12517-019-5013-9

Alvares, C. A., Stape, J. L., Sentelhas, P. C., De Moraes Gonçalves, J. L., & Sparovek, G. (2014). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 22(4), 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Andrade, M.A., Drummond, G.M., Domingues, S.A., Martins, C. S., & Franco, A. R. (2018). Espinhaço Range Biosphere Reserve Phase 2, MaB-*UNESCO*. Belo Horizonte, Minas Gerais, Brazil. Retrieved from https://reservasdabiosfera.org.br/wp-content/uploads/2021/11/Relatorio-2018-RBSE_-_PROPOSAL-PHASE-2_portugues.pdf. Accessed 10 November 2024.

Beskow, S., Mello, C. R., Norton, L. D., Curi, N., Viola, M. R., & Avanzi, J. C. (2009). Soil erosion prediction in the Grande River Basin, Brazil using distributed modeling. *Catena*, 79(1), 49-59. https://doi.org/10.1016/j.catena.2009.05.010

Costa, A. M., Viana, J. H. M., Evangelista, L. P., de Carvalho, D. C., Pedras, K. C., de Marco Horta, I., ... & Sampaio, J. L. D. (2017). Ponderação de variáveis ambientais para a determinação do Potencial de Uso Conservacionista para o Estado de Minas Gerais. *Geografias*, 14(1), 118–134. https://doi.org/10.35699/2237-549X..13439

Costa, A. M., Salis, H. H. C., Araújo, B. J. R. S., de Moura, M. S., da Silva, V. C., de Oliveira, A. R., ... & Viana, J. H. M. (2019). Potencial de uso conservacionista em bacias hidrográficas: estudo de caso para a bacia hidrográfica do rio Gualaxo do Norte - MG. Geografias, 27(2), 127–147. https://doi.org/10.35699/2237-549X.2019.19891

Costa, R. C. A., Pereira, G. T., Pissarra, T. C. T., Siqueira, D. S., Fernandes, L. F. S., Vasconcelos, V., ... & Pacheco, F. A. L. (2019). Land capability of multiple-landform watersheds with environmental land use conflicts. *Land use policy*, *81*, 689-704. https://doi.org/10.1016/j.landusepol.2018.11.041

Costa, T. R., da Silva, L. A., de Moura, C. C., de Souto Azevedo, C. H., Bueno, M. L., Mucida, D. P., ... & Gonzaga, A. P. D. (2023). Vulnerability of the Cerrado–Atlantic Forest ecotone in the Espinhaço Range Biosphere Reserve to climate change. *Theoretical and Applied Climatology*, *151*(3), 1151-1170. https://doi.org/10.1007/s00704-022-04321-z

Costa, A. M., de Moura, M. S., Navarro, I. F., da Silva, V. C., Pissarra, T. C. T., Valera, C. A., ... & Pacheco, F. A. L. (2024). Ecosystem services potential and soil conservation policies with emphasis on degraded pastures in Brazil. *Geography and Sustainability*. https://doi.org/10.1016/j.geosus.2024.07.010

Cunha, E. R. da, Bacani, V. M., & Panachuki, E. (2017). Modeling soil erosion using RUSLE and GIS in a watershed occupied by rural settlement in the Brazilian Cerrado. *Natural Hazards*, 85, 851 – 868. https://doi-org.ez36.periodicos.capes.gov.br/10.1007/s11069-016-2607-3

Deng, L., Sun, T., Fei, K., Zhang, L., Fan, X., Wu, Y., & Ni, L. (2020). Effects of erosion degree, rainfall intensity and slope gradient on runoff and sediment yield for the bare soils from the weathered granite slopes of SE China. *Geomorphology*, *352*, 106997. https://doi.org/10.1016/j.geomorph.2019.106997

Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA. (1999). Sistema brasileiro de classificação de solos. Brasília: Serviço de Produção de Informação.

Godoi, R. F., Rodrigues, D. B., Borrelli, P., & Oliveira, P. T. S. (2021). High-resolution soil erodibility map of Brazil. *Science of The Total Environment*, 781, 146673. https://doi.org/10.1016/j.scitotenv.2021.146673

Gorgens, E. B., Nunes, T. K. M. R., Mucida, D. P., Santana, R. C., Morais, M. S., Matosinhos, C.C., & Dutra, G. C. (2021). Núcleo de Zoneamento ambiental produtivo da UFVJM: bacia hidrográfica do Ribeirão Santana, MG. Coordenador: Eric Bastos Gorgens. - Diamantina: UFVJM/ PPGCF, 2021. 127 p. Retrieved from https://drive.google.com/drive/folders/12qnFBzvt2n7SzzqsmUQ4v5xu5spggn0o. Accessed 23 August 2024.

Guerra, C. A., Berdugo, M., Eldridge, D. J., Eisenhauer, N., Singh, B. K., Cui, H., ... & Delgado-Baquerizo, M. (2022). Global hotspots for soil nature conservation. *Nature*, *610* (7933), 693-698. https://doi.org/10.1038/s41586-022-05292-x

Freitas, I. C., Ribeiro, J. M., Araújo, N. C. A., Santos, M. V., Sampaio, R. A., Fernandes, L. A., ... & Frazão, L. A. (2020). Agrosilvopastoral Systems and Well-Managed Pastures Increase Soil Carbon Stocks in the Brazilian Cerrado. *Rangeland Ecology & Management,* 73(6), 776-785. https://doi.org/10.1016/j.rama.2020.08.001

Guedes, T. B., Azevedo, J. A., Bacon, C. D., Provete, D. B., & Antonelli, A. (2020). Diversity, endemism, and evolutionary history of montane biotas outside the Andean region. *Neotropical diversification: patterns and processes*, 299-328.10.1007/978-3-030-31167-4_13

Ghimire, M., Khanal, A., Bhatt, D., Dahal, D., & Giri, S. (2024). Agroforestry systems in Nepal: Enhancing food security and rural livelihoods–a comprehensive review. *Food and Energy Security*, *13*(1), e524. https://doi.org/10.1002/fes3.524

Huang, J. (2018). Assessment of potential changes in soil erosion using remote sensing and GIS: a case study of Dacaozi Watershed, China. *Environmental Monitoring and Assessment,* 190, 736. https://doi.org/10.1007/s10661-018-7120-6

Kebede, Y. S., Endalamaw, N. T., Sinshaw, B. G., & Atinkut, H. B. (2021). Modeling soil erosion using RUSLE and GIS at watershed level in the upper beles, Ethiopia. *Environmental Challenges,* 2, 100009. https://doi.org/10.1016/j.envc.2020.100009

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, 15(3), 259-263. DOI: https://doi.org/10.1127/0941-2948/2006/0130

Lense, G. H. E., Moreira, R. S., Parreiras, T. C., Santana, D. B., Bolelli, T. D. M., & Mincato, R. L. (2020). Water erosion modeling by the Erosion Potential Method and the Revised Universal Soil Loss Equation: a comparative analysis. *Revista Ambiente & Água*, 15(4). https://doi.org/10.4136/ambi-agua.2501

Mannigel, A. R., Passos, M., Moreti, D., & da Rosa Medeiros, L. (2002). Fator erodibilidade e tolerância de perda dos solos do Estado de São Paulo. *Acta Scientiarum*, 24(5), 1335-1340

Meybeck, A., Cintori, L., Cavatassi, R., Gitz, V., Gordes, A., Albinelli, I., ... & Boscolo, M. (2024). Natural resources management for resilient inclusive rural transformation. *Global Food Security*, *42*, 100794. https://doi.org/10.1016/j.gfs.2024.100794

Michalk, D. L., Kemp, D. R., Badgery, W. B., et al. (2019). Sustainability and future food security—a global perspective for livestock production. *Land Degradation & Development*, 30, 561-573. https://doi.org/10.1002/ldr.3217

Michalopoulou, M., Depountis, N., Nikolakopoulos, K., & Boumpoulis, V. (2022). The significance of digital elevation models in the calculation of LS factor and soil erosion. *Land*, *11*(9), 1592.

Montagnini, F., & del Fierro, S. (2024). Agroforestry systems as biodiversity Islands in productive landscapes. In *Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty* (pp. 551-588). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-54270-1_19

Morandi, D. T., Menezes, E. S., França, L. C. D. J., Mucida, D. P., Silveira, L. P. D., & Silva, M. D. D. (2018). Diagnóstico da antropização em área de preservação permanente em segmento do rio Jequitinhonha (MG). *BIOFIX Scientific Journal*, 3(2), 252-259. http://dx.doi.org/10.5380/biofix.v3i2.60177

Morellato, L. P. C., Silveira, F. A. O. (2018). Plant life in Campo Rupestre: new lessons from an ancient biodiversity hotspot. *Flora.* https://doi-org.ez36.periodicos.capes.gov.br/10.1016/j.flora.2017.12.001

Moura, M. S., Silva, V. C., Pacheco, F. A. L., Fernandes, L. F. S., Pissarra, T. C. T., & da Costa, A. M (2024). Beyond land use planning and ecosystem services assessment with the conservation use potential framework: A study in the Upper Rio das Velhas basin, Brazil. *Science of The Total Environment*, v. 923, p. 171437-16. https://doi.org/10.1016/j.scitotenv.2024.171437

Mucida, D. P., Gorgens, E. B., Rech, A. R., Christofaro, C., da Silva, R. S., Pereira, I. M., ... & de Jesus França, L. C. (2023). Designing optimal agrosilvopastoral landscape by the potential for conservation use in Brazil. *Sustainable Horizons*, *5*, 100045. https://doi.org/10.1016/j.horiz.2022.100045

Oberreich, M., Steinhoff-Knopp, B., Burkhard, B., & Kleemann, J. (2024). The research gap between soil biodiversity and soil-related cultural ecosystem services. *Soil Systems*, *8*(3), 97. https://doi.org/10.3390/soilsystems8030097

Panagos, P., Borrelli, P., & Poesen, J. (2019). Soil loss due to crop harvesting in the European Union: A first estimation of an underrated geomorphic process. *Science of The Total Environment*, 664, 487-498. https://doi.org/10.1016/j.scitotenv.2019.02.009

Panagos, P., Borrelli, P., Matthews, F., Liakos, L., Bezak, N., Diodato, N., & Ballabio, C. (2022). Global rainfall erosivity projections for 2050 and 2070. *Journal of Hydrology*, *610*, 127865. https://doi.org/10.1016/j.jhydrol.2022.127865

Pandey, S., Kumar, P., Zlatic, M., Nautiyal, R., & Panwar, V. P. (2021). Recent advances in assessment of soil erosion vulnerability in a watershed. *International Soil and Water Conservation Research*, *9*(3), 305-318. https://doi.org/10.1016/j.iswcr.2021.03.001

Pereira, M. D. R., & Cabral, J. B. P. (2021). Perda de solo no alto curso das bacias hidrográficas dos ribeirões Taquaruçu Grande e Taquaruçuzinho, Palmas (TO). *Revista Brasileira de Geografia Física*, 14(01), 332-339. https://doi.org/10.26848/rbgf.v14.1.p332-339

Pinto, G. S., Servidoni, L. E., Lense, G. H. E., Moreira, R. S., & Mincato, R. L. (2020). Estimativa das perdas de solo por erosão hídrica utilizando o Método de Erosão Potencial. *Revista do departamento de geografia*, 39, 62-71. https://doi.org/10.11606/rdg.v39i0.160233

Rapini, A., Bitencourt, C., Luebert, F., & Cardoso, D. (2021). An escape-to-radiate model for explaining the high plant diversity and endemism in campos rupestres. *Biological Journal of the Linnean Society*, 133(2), 481-498. https://doi.org/10.1093/biolinnean/blaa179

Rehman, M. A., Abd Rahman, N., Ibrahim, A. N. H., Kamal, N. A., & Ahmad, A. (2024). Estimation of soil erodibility in Peninsular Malaysia: A case study using multiple linear regression and artificial neural networks. *Heliyon*, *10*(7). https://doi.org/10.1016/j.heliyon.2024.e28854

Rocha, G. C., & Sparovek, G. (2021). Scientific and technical knowledge of sugarcane cover-management USLE/RUSLE fator. *Scientia Agricola*, 78(suppl 1), e20200234. https://doi.org/10.1590/1678-992X-2020-0234

Santos Neto, J. R. dos., & Christofaro, C. (2020). Erosividade Da Chuva Na Bacia Hidrográfica Do Rio Araçuaí-Mg. *Boletim de Geografia*, 37(3), 40-50. https://doi.org/10.4025/bolgeogr.v37i3.37522

Scalco, R. F., & Souza, D. E. (2019). Área de Proteção Ambiental Estadual das Águas Vertentes: instrumentos de gestão e potencial turístico. *Caderno Virtual de Turismo*, 18(3), 107–128. http://dx.doi.org/10.18472/cvt.18n3.2018.1278

Sherren, K., Fischer, J., & Fazey, I. (2012). Managing the grazing landscape: insights for agricultural adaptation from a mid-drought photo-elicitation study in the Australian sheep-wheat belt. *Agricultural Systems*, 106, 72-83. https://doi.org/10.1016/j.agsy.2011.11.001

Silva, A. C., Horàk-Terra, I., Barral, U. M., Costa, C. R., Gonçalves, S. T., Pinto, T., ... & Vidal-Torrado, P. (2020). Altitude, vegetation, paleoclimate, and radiocarbon age of the basal layer of peatlands of the Serra do Espinhaço Meridional, Brazil. *Journal of South American*

Earth Sciences, 103, 102728. https://doi.org/10.1016/j.jsames.2020.102728

Thomas, J., Joseph, S., & Thrivikramji, K. P. (2018). Assessment of soil erosion in a tropical mountain river basin of the southern Western Ghats, India using RUSLE and GIS. *Geoscience Frontiers*, 9(3), 893-906. https://doi.org/10.1016/j.gsf.2017.05.011

Tesfaye, W., Elias, E., Warkineh, B., Tekalign, M., & Abebe, G. (2024). Modeling of land use and land cover changes using Google Earth Engine and machine learning approach: implications for landscape management. *Environmental Systems Research*, *13*(1), 31. https://doi.org/10.1186/s40068-024-00366-3

UNESCO. (2024). Man and the Biosphere Programme (MAB) interactive map. Retrieved November 26, 2024, from https://www.unesco.org/en/mab/map

Vasques, I. C. F., Souza, A. A., Morais, E. G., Benevenute, P. A., da Silva, L. D. C., Homem, B. G., ... & Silva, B. M. (2019). Improved management increases carrying capacity of Brazilian pastures. *Agriculture, Ecosystems & Environment*, 282, 30-39. https://doi.org/10.1016/j.agee.2019.05.017

Viana, C. M., Freire, D., Abrantes, P., Rocha, J., & Pereira, P. (2022). Agricultural land systems importance for supporting food security and sustainable development goals: A systematic review. *Science of the total environment*, *806*, 150718. https://doi.org/10.1016/j.scitotenv.2021.150718

Zhang, Q. F. (2024). Producers' transition to alternative food practices in rural China: social mobilization and cultural reconstruction in the formation of alternative economies. *Agriculture and Human Values*, *41*(2), 615-630. https://doi.org/10.1007/s10460-023-10509-4

Zhou, Z., Sun, X., Zhang, X., & Wang, Y. (2022). Inter-regional ecological compensation in the Yellow River Basin based on the value of ecosystem services. *Journal of Environmental Management*, *322*, 116073. https://doi.org/10.1016/j.jenvman.2022.116073