Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission – Land Use Planning

Disposal of solid waste from civil construction: a screening proposal for a suitability system and case study in Nepomuceno, Minas Gerais

Luana Sousa Costa[(1)], Marcelo Henrique Procópio Pelegrino[(1)], Bruno Silva Villela[(1)], Maria Eduarda Carvalho Monteiro[(1)], Raísa Brito Vilela[(1)], Daniela de Fátima Pedroso[(2)], Iris Helena Antunes Naime[(3)], Ivan Massimo Pereira Leite[(2)], Bruno Montoani Silva[(1)], Nilton Curi[(1)] and Michele Duarte de Menezes[(1)*]

[(1)] Universidade Federal de Lavras, Departamento de Ciência do Solo, Lavras, Minas Gerais, Brasil.
[(2)] Consórcio Regional de Saneamento Básico - CONSANE, Lavras, Minas Gerais, Brasil.
[(3)] Orizon Meio Ambiente Ltda, Paulínia, São Paulo, Brasil.

*** Corresponding author:**
E-mail: michele.menezes@ufla.br

Received: May 11, 2023

Approved: October 04, 2023

How to cite: Costa LS, Pelegrino MHP, Villela BS, Monteiro MEC, Vilela RB, Pedroso DF, Naime IHA, Leite IMP, Silva BM, Curi N, Menezes MD. Disposal of solid waste from civil construction: a screening proposal for a suitability system and case study in Nepomuceno, Minas Gerais. Rev Bras Cienc Solo. 2024;48:e0230044
https://doi.org/10.36783/18069657rbcs20230044

Editors: José Miguel Reichert and Ricardo Simão Diniz Dalmolin .

ABSTRACT: Most Brazilian municipalities do not have regulated areas for solid waste disposal in civil construction. Usually, residues are disposed of vacant lots and dumps, posing risks to the population health and the environment. Soils are the primary means for the disposal or recycling of waste, highlighting the importance of well-characterized soils and their respective landscape. This study aimed to establish a land suitability system for solid residues in civil construction and apply such information in a case study in Southeastern Brazil. An unprecedented digital soil map with a resolution of 30 m was created using the random forest classifier algorithm and soil field prospection information. A guide listing favorable soil-landscape attributes that most prevent soil erosion, water bodies or water table contamination was elaborated and discussed. Thus, such information was linked through a suitability system to classify areas with potential for receiving waste on a daily volume basis as follows: large size: >500 m^3 day^{-1}, medium size: >100 m^3 day^{-1} and <300 m^3 day^{-1}, and small size <100 m^3 day^{-1}. Topography and soil depth were the most limiting factors of the areas in the case study. The proposed attributes as criteria for the suitability system complement the current state legislation. A total of 236 ha closer to the urban perimeter connected by roads in good condition were classified as suitable for managing medium- and small-scale daily volume, whose destination might reduce transportation and installation costs in the study area.

Keywords: land-use planning, soil survey, random forest, environmental legislation.

INTRODUCTION

Historically, suitability systems that applied soil-landscape information as a fundamental basis have mainly focused on food, fuel, or fiber production (Ramalho Filho and Beek, 1995; Costa et al., 2009; Amaral, 2011; Silva et al., 2013; Jamil et al., 2018; Taveira et al., 2019). However, soils have faced unprecedented pressures concerning degradation and urbanization (Viscarra-Rossel et al., 2016), increasing the challenge of environmental sustainability to reduce the impacts on ecosystem services (McBratney et al., 2014). In this sense, Pedron et al. (2006) developed a system considering potential urban use for waste disposal, urban construction, urban agriculture, and environmental preservation groups. Oliveira et al. (2016) developed a land-suitability system for waste disposal, emphasizing the installation of septic systems. Ghosh and Nanda (2016) combined favorable soil-landscape characteristics with low population density to create a suitability system for general waste disposal in India. With the rapid urbanization and growing population, Brazilian municipalities need a specific guide to regulate solid waste disposal, especially from civil construction.

Most Brazilian municipalities do not have regulated areas for solid waste disposal in civil construction. Usually, the waste is discarded in vacant lots or dumps, bringing risks to the population health and the environment (Abrelpe, 2019). In general, one of the significant impact is the large volume generated of such wastes, being managed as low-hazardous. However, they might contain organic materials, hazardous products, and various packaging that can accumulate water, favoring insect proliferation and other disease vectors, such as *Aedes aegypti* (Karpinski et al., 2008), a recurrent problem in Brazil.

The regulatory legislation concerning solid waste disposal of civil construction had an important milestone in 2002, through resolution No. 307/2002 of the National Environment Council – CONAMA, which established that the generating source of the waste was responsible for the proper disposal. Nevertheless, most Brazilian municipalities dispose of the waste in irregular locations. Municipalities urban cleaning service is not considered legally responsible for collecting this waste. In 2018, 122,012 Mg day^{-1} of waste were abandoned on roads and other public places. In the southeastern region of Brazil, cleaning services have collected 63,679 Mg day^{-1} of waste, equivalent to a per capita collection of 0.726 kg inhabitant^{-1} day^{-1} (Abrelpe, 2019).

In addition to federal regulations, the state of Minas Gerais has two essential guidelines for solid waste management: a) the normative deliberation of the State Environmental Policy Council – Copam No. 244 of 2022, which establishes guidelines for the definition of areas for the final disposal of the urban solid waste; and b) the Federal law No. 12,305 of 2010 (Brasil, 2010), consisting of the national solid waste management policies as a mandatory mean of integrating management regulations. Management regulations must identify the most appropriate areas for adequate waste disposal. Federal law No. 14,206 of 2020 set a deadline for implementing the environmentally appropriate final disposal of municipalities with a population of up to 50,000 until August 2, 2024. Additionally, the Brazilian Standard – NBR 15,113:2004 establishes the minimum requirements for designing, implementing, and operating landfills for solid waste from civil construction and inert waste. Notably, NBR 15,113:2004 does not recommend any waterproofing treatment for civil construction landfills, increasing the importance of soil characterization to ensure the suitability of facilities and environmental sustainability.

The current resolution Copam No. 244 of 2022 only suggests that solutions concerning waste disposal must be regionalized, but detailed guidance about the proper places for disposal is not provided. Soil surveys have stood out considering the tools supporting an adequate environmental and land-use diagnosis (Menezes et al., 2009; Stoorvogel et al., 2017). A complete soil survey report carries in-depth information about the morphological, physical, and chemical properties of a soil profile, attached to a typical landscape of their occurrence, encompassing the environment of each soil class (Resende et al., 2014).

Such variation imposes different suitability for waste disposal directly on soil (Oliveira et al., 2016). More recently, digital soil mapping techniques have been applied based on the generalization of the traditional five factors of soil formation proposed by Jenny (1941), from which seven predictive factors (environmental covariates) in digital format are derived from soil, climate, organisms, relief, parent material, time, and spatial/geographical position (McBratney et al., 2003), constituting the so-called Scorpan model. From this framework, soil can be spatially predicted from its properties and environmental covariates, which are proxies of state factors for the spatial association. This additional model input is less connected to soil-forming processes but improves spatial predictions using closely measured soil sample information (Wadoux et al., 2020).

Soils are the primary mean of disposal or recycling of waste due to their ability to promote: a) the modification of organic and inorganic compounds through chemical reactions and physical or biological processes (Streck et al., 2018); b) filtering, reducing contamination and preventing many pollutants from reaching groundwater (Oliveira et al., 2016); and c) the remediation process since its ecosystem attributes and services contribute to the immobilization, dissipation, and filtering of contaminants. In this context, carrying out a soil survey is a strategic step as it characterizes the spatial variability of soils since their properties influence the retention and leaching of elementals or molecules, erosion, and surface runoff potential. However, the only harmonized soil survey available for the state of Minas Gerais presents a small scale (1:650,000) (UFV/CETEC/UFLA/FEAM, 2010). Soil surveys at more detailed scales compatible with solid waste management purposes are necessary.

According to the national solid waste policy (No. 12,305 of 2010), all municipalities must plan for integrated solid waste management, including identifying environmentally appropriate areas for final disposal. Small and medium-sized municipalities do not have sufficient financial resources and technical staff for the efficient and sustainable management of solid waste. Thus, a consortium is an alternative tool to universalize services (Ventura et al., 2020). To answer a demand from Regional Basic Sanitation Consortium (CONSANE) for policy-making in co-creation and municipalities, this study aimed to develop a suitable system for solid waste disposal in civil construction. In addition, the system was applied in the municipality of Nepomuceno – Minas Gerais State as a study case.

MATERIALS AND METHODS

Study area

The selected study area was Nepomuceno Municipality in the state of Minas Gerais. It is located between latitudes 469927 and 484733 m and longitudes 7672934 and 7637880 m, zone 23S (UTM coordinates, *datum* WGS 84) (Figure 1), with altitudes ranging from 756 to 1136 m. The municipality has a total of 583.78 km^2 of area and has 26,769 inhabitants (IBGE, 2020). The pilot area contains physiographic features representative of the Campos das Vertentes region, where the interpretations generated here could be extrapolated. Nepomuceno plays an essential sanitary role for the surrounding municipalities due to sanitary and industrial landfills installed for receiving waste. The climate is characterized as Cwb according to the Köppen classification system (Alvares et al., 2013) (mesothermal with mild and humid summers and dry winters). The mean annual temperature is 18.9 °C, and the annual rainfall is 1,630 mm. Granite, gneisses, migmatites, quartzites, and ultramafic rocks mainly represent geology. The native vegetation is represented by subperennial tropical forests and savannas (Cerrado) with pastures and cultivated areas consisting mainly of coffee plantations (Trouw et al., 2007). Thus, applying the suitability system in landscapes with similar conditions to those above mentioned is recommended.

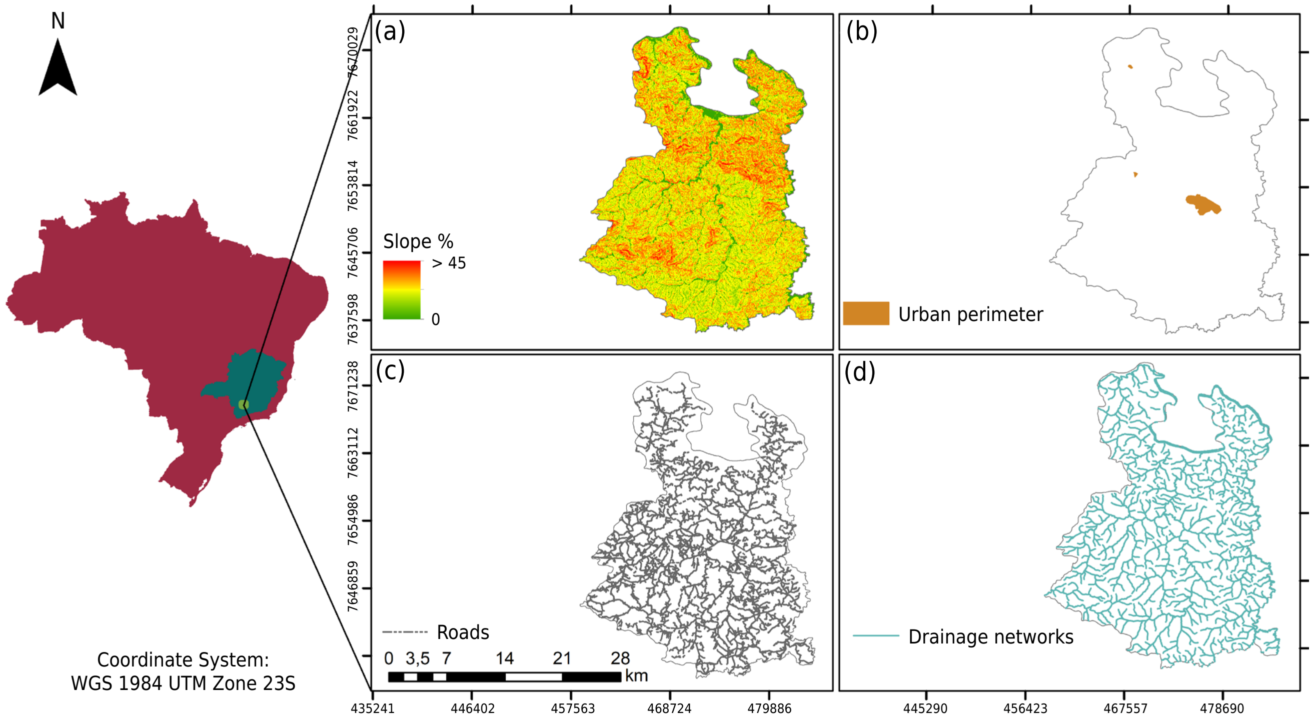

Figure 1. Location map of the municipality of Nepomuceno. (a) slope range; (b) urban perimeter; (c) road infrastructure; and (d) drainage networks. Adaptad from Spatial Data Infrastructure of the State Environment and Water Resources System (IDE- Sisema).

Initially, parameters were applied according to the normative deliberation of the State Environmental Policy Council – Copam No. 118/2008. Although revoked, the guidelines bring the concept of adequacy of the final disposal of urban solid waste in the State of Minas Gerais (Table 1). Based on these criteria, the spatial pre-definition of areas with the potential for allocating civil construction landfills was carried out.

Slope was calculated from the digital elevation model (DEM) with 30 m of resolution obtained from the Shuttle Radar Topography Mission (SRTM) in the SAGA geographic information system (System for Automated Geoscientific Analysis) (Conrad et al., 2015). Information about the current land-use and coverage of the soil, hydrography, vegetation, and roads (including the local roads) (Figure 1) were obtained from the Spatial Data Infrastructure of the State Environment and Water Resources System (IDE- Sisema) (Sisema, 2019) at 1:50.000 scale.

Areas considered inapt or possessing any restriction according to Copam No. 118/2008 were firstly excluded (Table 1). For that, the weighted overlay tool from ArcGIS version 10.1 (ESRI®) was applied using the digital layers of the slope, location of urban centers, hydrography, and road infrastructure.

Digital soil mapping

Prospecting locations were previously selected for field campaigns from the Latin hypercube conditioned by the cost algorithm developed in the R software (R Development Core Team, 2009) through the *clhs* package (Minasny and McBratney, 2006; Roudier, 2021). The following georeferenced digital information was used as input data in the algorithm: a) terrain attributes that have significance regarding soil-landscape (DEM, slope, surface texture of the terrain, and topographic wetness index); b) information that might affect the cost of access of a given location: the Euclidean distance function was applied to the road infrastructure layer in ArcGIS version 10.1 (ESRI®) to create weights based on the distances from the roads (the longer the distance, the higher the weight assigned, the higher the cost of access) (Roudier et al., 2012; Silva et al., 2015).

Table 1. Criteria used to delimit areas with potential for allocating civil construction landfills according to Normative Deliberation Copam No. 118/2008

Weighted-overlay analysis parameters	Criteria
Distance from urban centers	1 km > suitable location <10 km
Distance from roads	Suitable location <100 m
Distance from water bodies	Suitable location >500 m
Slope	Suitable location <30 %

In 25 soil locations, morphological description and sample collections were performed according to Santos et al. (2015). Soil texture analysis was done using the pipette method (Gee and Bauder, 1986) at 0.00-0.20, 0.40-0.70, and 1.00-1.20 m soil layers. Soils were classified according to the Brazilian Soil Classification System (Santos et al., 2018) and US Soil Taxonomy (Soil Survey Staff, 2014). Additionally, 18 legacy soil profiles containing full descriptions were obtained from Villela (2020) to compose the complete soil database.

Environmental covariates

The DEM with 30 m resolution was obtained from the Shuttle Radar Topography Mission (SRTM). Images were pre-processed to fill gaps and make the model hydrologically consistent. From the DEM, the covariates related to topography were calculated in the SAGA GIS software (Conrad et al., 2015): aspect, valley depth, channel network base level (cnbl), channel network distance (cnd), LS factor, multiresolution index of valley bottom flatness (mrvbf), SAGA topographic wetness index (stwi), slope, and terrain surface texture (texture).

Airborne gamma-ray spectrometry survey was used as a proxy of soil parent material (Lacoste et al., 2011; Weihermann et al., 2016). This sensor measures the natural radiation emanating from the Earth's surface from the decay series of K (%), Th (ppm), and U (ppm) in the first 0.30 m of the surface. Standard processing for aerial geophysical surveys was performed using OASIS MONTAJ 9.7 software (Smethurst, 2005). The interpolation of the dataset was calculated using minimum curvature in regular grids of 100 m (1/4 to 1/5 of the spacing of the flight lines), generating the K (%), Th, and U (ppm) concentration raster grids (IAEA, 2003). With the grid knitting tool, the resulting grids were fixed. Finally, the total gamma-ray flux (dose) was calculated based on the weighted additions of radioactive elements using the formula (Wilford, 2012): Dose = 13.078 K (%) + 5.67 U (ppm) + 2.49 Th (ppm). Concentrations of Th and U generally increase, and K decreases during bedrock weathering and soil formation (Wilford and Minty, 2006).

Annual precipitation data was obtained through WorldClim 2.1 (Fick and Hijmans, 2017) to represent climate as a soil-forming factor. Soil organic carbon stock was obtained from Gomes et al. (2019) due to the influence of organisms for soil characteristics.

Random forest: input information, modeling, and accuracy assessment

Firstly, a circular buffer with a 30 m radius around each soil prospection point was created. This buffer consisted of a polygon used to overlay a raster map to extract pixels within this area. Thus, it was assumed that the same soil class for each pixel within this buffer polygon increased the training dataset size. Results have suggested that this task increases the accuracy of random forest (RF) (Pelegrino et al., 2016; Machado et al., 2019). In this study, the buffer increased the database for 131 soil input information (Table 2) over the 41 field sampling.

Secondly, since the RF algorithm is sensitive to different training dataset strategies (Machado et al., 2019), the Spearman correlation test was performed to reduce the multicollinearity among environmental covariates (the ones with more than 80 % correlation were excluded) (Koreen and Richardson, 2015).

Table 2. Soil database used for mapping, soil classes (Brazilian Soil Classification System and U.S. Soil Taxonomy between parentheses), number of field prospections, and samples number extracted from the buffer

Soil class	Number of field prospections	Number of samples extracted with the 30 m buffer
Cambissolo Háplico Tb Distrófico (Dystrustept)	5	12
Floodplain soils complex	5	10
Latossolo Amarelo Distrófico (Hapludox)	3	6
Latossolo Vermelho Distrófico (Acrudox)	20	43
Latossolo Vermelho-Amarelo Distrófico (Hapludox)	3	7
Nitossolo Vermelho Distrófico (Rhodudult)	1	3
Argissolo Vermelho Distrófico (Rhodudult)	2	5
Argissolo Vermelho-Amarelo Distrófico (Hapludult)	2	4
Total	41	131

Furthermore, the soil map was obtained from spatial prediction with the RF algorithm using *randomForest* package (Breiman, 2001) in the R software (R Development Core Team, 2009). For this study, the *ntree* optimal parameter value found was 500, from the iterations in the caret package and better accuracy return. The *mtry* hyperparameter controlled the number of sample variables. Thus, the number of variables used for each tree was the square root of the total number of variables (*mtry* = 4) (Machado et al., 2019). The class of each sample is then determined by the most frequent type from the trees constructed. Two-thirds of the samples were used to build the trees (model), and the remaining third were for validation and called out-of-bag (OBB) calculation. The OBB samples were inserted into the decision tree, and a predicted class was assigned to each OOB sample. A single model was obtained with the RF result, accompanied by the aggregate error estimated and the overall OBB estimated error rate (Heung et al., 2014).

The accuracy of the digital soil map was assessed by overall accuracy (OA) and Kappa index (KI) from a confusion matrix. The OA was calculated from the sum of the main diagonal components of the confusion matrix divided by the total number of samples used in the validation. The KI, a measure of agreement, considered all elements of the confusion matrix, the number of soil classes, and the samples correctly classified. Values range from -1, where there is more significant disagreement, to 1, suggesting excellent agreement (Landis and Koch, 1977; Pelegrino et al., 2016).

Suitability system for solid waste disposal from civil construction

Suitability classes were defined according to the potential or not for receiving waste in daily volume: large size: >500 m^3 day^{-1}, medium size: >100 and <300 m^3 day^{-1}, small size <100 m^3 day^{-1}, and inadequate (lands that are not supposed to receive any waste). The greater the volume, the higher the potential risk of environmental contamination. The potential for receiving waste in daily volume was established by Copam No. 217/2017, which deals with aspects according to size criteria, polluting potential, and location criteria. Thus, the areas that bring together all the attributes favorable to waste disposal will be classified as those with the greatest volume reception capacity.

Soil and landscape properties obtained from soil survey and geoprocessing analysis related to water dynamics or soil erosion were analyzed. Favorable attributes are those that most prevent soil erosion and or water bodies or water table contamination. The increasing of limiting attributes decreases the volume of waste suitability. The most limiting attribute is the determinant to fit a given soil-landscape in each suitability class. A final guide table is suggested containing a broad combination of soil features applied in the study case.

RESULTS

Suitability system

Table 3 shows the suitability system of waste disposal for civil construction. The latter establishes criteria for classification according to the size and polluting potential of environmental licensing of facilities and activities that use environmental resources in Minas Gerais, Brazil. The values was adapted from Oliveira et al. (2016) and Streck et al. (2018). General description of the selected soil and terrain characteristics of the proposed system is presented further:

- Soil depth: is related to the volume of soil available for the adsorption, attenuation, and stability of residues. This natural attenuation generally involves transferring and stabilizing the contaminant from one location to another (from the surface to the subsurface, for example). The main advantage is reducing and diluting the pollutants efficiently and continuously (Andrade et al., 2010). Studies show that leaches from civil construction waste may contain significant metallic contaminants (Torgal and Jalali, 2011; Staunton et al., 2015). High concentrations of As, Ba, Cd, Co, Sb, Se, and Tl were found in slugs collected in civil construction waste disposal areas compared to slugs collected in control areas (Staunton et al., 2015). Although there are few studies about the polluting potential, little evidence reinforces the need to consider the remedial role of soil depth when characterizing sites with the potential to receive waste.

- Soil texture: consists of the proportions of soil mineral fractions with a diameter smaller than 2 mm, whose classifications based on the textural triangle are clayey or very clayey (clay content greater than 350 g kg^{-1}), loam (less than 350 g kg^{-1} of clay and more than 150 g kg^{-1} of sandy, excluding sand fraction), and sandy (sand fraction). The tiniest fractions are responsible for the higher sorption, retention, and inactivation of residues.

- Textural gradient: consists of the accumulation of clay at the subsurface, resulting in a reduction of soil permeability at depth (B horizon), contributing to increasing the lateral flow and surface runoff of water, increasing susceptibility to erosion and risk of contamination of adjacent areas or watercourses (Streck et al., 2018).

- Soil drainage: refers to the speed of water flowing through the soil infiltration, affecting its moisture regime. Drainage provides an indication of soil permeability as well as the risk of groundwater contamination.

- Water table seepage: refers to the presence and depth of occurrence of the water table, where areas with its level close to the surface should be avoided, as transport of contaminants in solution may occur.

- Perched water table: its presence or absence is observed, being more frequent in soils with substantial physical impedance or abrupt textural gradient. Its occurrence can lead to the transport of contaminants in solution and lateral flow.

- Flood risk: areas subject to flooding are inadequate for waste disposal due to the risk of contaminants transportation by water. Redoximorphic soil colors (Kämpf and Curi, 2012) can help to indicate flood events or locals with a higher probability of their occurrence.

- Local relief and slope: related to the conformation of the soil surface. The steeper the slope, the greater the risks of erosion and contamination of adjacent areas and watercourses. Furthermore, this information is helpful from the point of view of adjustments for installing landfills or assessment improvement. Relief phases considered were: flat (0-3 % slope), gently undulated (3-8 %), undulated (8-20 %), and strongly undulated (20-30 %, according to current legislation, wastes could not be disposed in slopes greater than 30 %), and strongly undulated to mountainous (>30 %).

According to Copam deliberation No. 217/2017 for civil construction landfills, earthworks are not recommended, and the waste should be deposited directly on the soil surface, so stoniness was not included as an attribute in the suitability system.

Digital soil mapping

With the performance of Spearman correlation, the following environmental covariates were excluded: channel network base level (cnbl), channel network distance (cnd), and valley depth. This previous selection, along with the iterative steps of the RF algorithm, ensures using the most adapted environmental covariates for the study area. Thus, the spatial prediction of soils in the Nepomuceno municipality can be viewed in figure 2. Estimated OBB error was 6.82 %, and both overall accuracy and kappa index were 0.95, indicating a good accuracy of the predictive model. The RF algorithm and environmental covariates have demonstrated their ability to stratify environments and predict soil classes with adequate accuracy (Machado et al., 2019; Carvalho Junior et al., 2020).

Latossolos Vermelhos Distróficos (Acrudox), *Latossolos Vermelho-Amarelos Distróficos* (Hapludox), and *Latossolos Amarelos Distróficos* (Hapludox) (78.90 % of the area) occurred mainly in undulated relief on more elongated smoothed slopes, which is the predominant landscape condition in the municipality. *Cambissolos Háplicos Tb Distrófico* (Dystrustep) corresponded to the second-largest geographic expression in the municipality, totaling 11.47 % of the area, and occurred mainly in undulated and strongly undulated relief. Floodplain soils complex (8.93 %) corresponded to those environments closer to water bodies in flat or concave relief that leads to water stagnation, causing iron and manganese reduction (greyish soils) or organic carbon accumulation (organic soils). *Argissolos Vermelhos Distróficos* (Rhodudult) and *Argissolos Vermelho-Amarelos Distróficos* (Hapludult) occupied 0.7 % of the area, mainly in undulated relief. They present clay content increasing in depth, with B horizon presenting a blocky structure, decreasing the permeability compared to A horizon (granular structure).

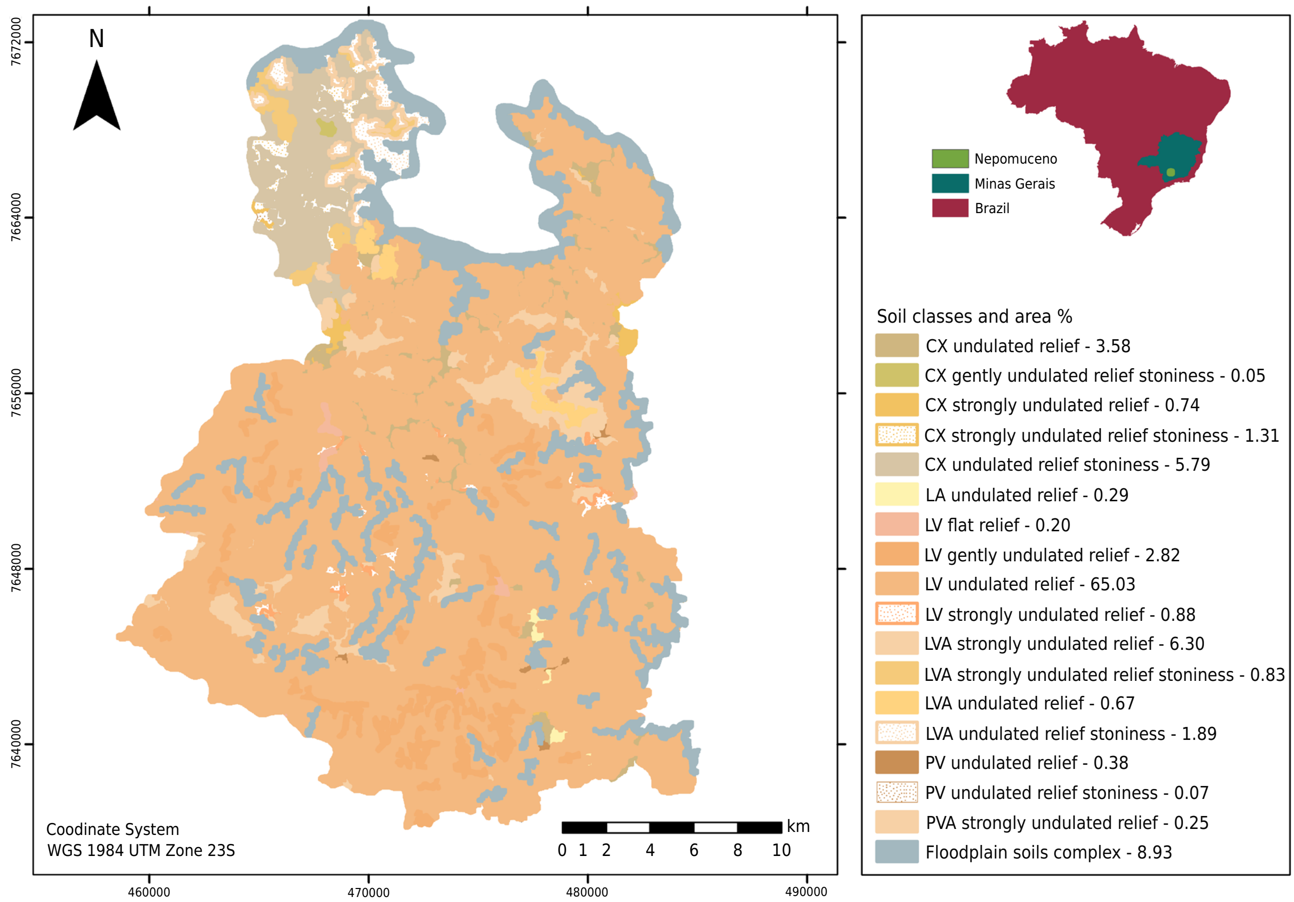

Figure 2. Soil map of the municipality of Nepomuceno. CX: *Cambissolo Háplico Tb Distrófico* (Dystrustept); LA: *Latossolo Amarelo Distrófico* (Hapludox); LV: *Latossolo Vermelho Distrófico* (Acrudox); LVA: *Latossolo Vermelho-Amarelo Distrófico* (Hapludox); PV: *Argissolo Vermelho Distrófico* (Rhodudult); PVA: *Argissolo Vermelho-Amarelo Distrófico* (Hapludult).

Table 3. Guide table for the suitability system for disposal of civil construction waste

Soil and landscape attributes	Large, medium, and small size	Medium and small size	Small size	Inadequate
Soil depth	>1.50 m	1.00-1.50 m	0.50-1.00 m	<0.50 m
Soil texture	Clayey	Loam	Loam	Sandy
Soil textural gradient	Without or gradual clay increase	With gradient, being abrupt at depth >1.00 m	With gradient, being abrupt at depth >1.00 m	Without
Drainage class	Excessive, strong or accentuated	Well to moderate	Imperfect	Poor or very poor
Water table seepage	Absent or >1.80 m	Absent or 1.00-1.80 m	<1.00 m	Superficial
Perched water table	Absent	Absent	Present	Present
Flood risk	Null	Null	Rare	From occasional to frequent
Local relief and slope	Flat to gently undulated (<8 %)	Undulated (8-20 %)	Strongly undulated (20-30 %)	Strongly undulated to steep (>30 %)

Large size: >500 m^3 day^{-1}, medium size: >100 and <300 m^3 day^{-1}, and small size <100 m^3 day^{-1} (Copam No. 217/2017). Values adapted from Streck et al. (2018) and Oliveira et al. (2016).

Based on the guide table (Table 3), field campaigns, and the soil map of the municipality of Nepomuceno (Figure 3), the suitability system was applied in areas previously selected according to the normative deliberation Copam 108/2008 (Table 1). The weighted overlap excluded 95 % of the municipality that does not comply with the legislation. The remaining areas were then classified according to the potential volume of waste received per day (Figure 3).

DISCUSSION

Latossolos Vermelhos Distróficos (Acrudox) are very weathered-leached, thicker, have uniform clay content in-depth, and have granular structure in the B horizon. Thus, they are porous soils, mainly in the subsurface, which gives them high permeability (Ferreira, 1999). Their physical properties allied to gentle and stable relief of occurrence decrease susceptibility to erosion. In addition, their thickness contributes to a large volume of soil for waste remediation. *Cambissolos Háplicos Tb Distrófico* (Dystrustept) mainly occurred in the steepest portions of the relief. They present an incipient degree of development and higher values of silt/clay ratio (>0.6 in the B horizon) that confer greater instability and increase erosion susceptibility. *Cambissolos Háplicos Tb Distrófico* (Dystrustept) presented a loam texture, with stoniness in some areas, and additionally, a small solum depth was observed, which in dissected reliefs are shallower soils.

Where the granite-gneiss emerges, there is an occurrence of steeper relief and the occurence of *Cambissolos Háplicos Tb Distróficos* (Dystrustept) is favored. The occurrence of ultramafic, mafic, and schist rocks and gentle relief (Oliveira et al., 1983) favors the occurrence of *Latossolos Vermelhos Distróficos* (Acrudox). It has been reported the predominance of *Latossolos Vermelhos Distróficos* (Acrudox) formed over gabbro, whose rock is more easily weathered than other ones reported in the region (Resende et al., 2011; Curi et al., 2020), corroborating with the occurrence of Acrudox and Dystrustept in the digital soil map.

Argissolos Vermelhos Distróficos (Rhodudult) and *Argissolos Vermelho-Amarelos Distróficos* (Hapludult) are well-drained (Figure 3), they presented clay content increasing in depth, with a gradual or abrupt textural gradient at depths >1.00 m. Stoniness and rocky outcrops were observed in some areas. Although the *Nitossolos Vermelhos Distróficos* (Rhodudult) appear in the training dataset, the RF algorithm did not perform its spatial prediction of the lower density of its occurrence, hampering the learning process of the algorithm. This limitation concerning the natural imbalance dataset has been previously reported by Sharififar et al. (2019) and Taghizadeh-Mehrjardi et al. (2020).

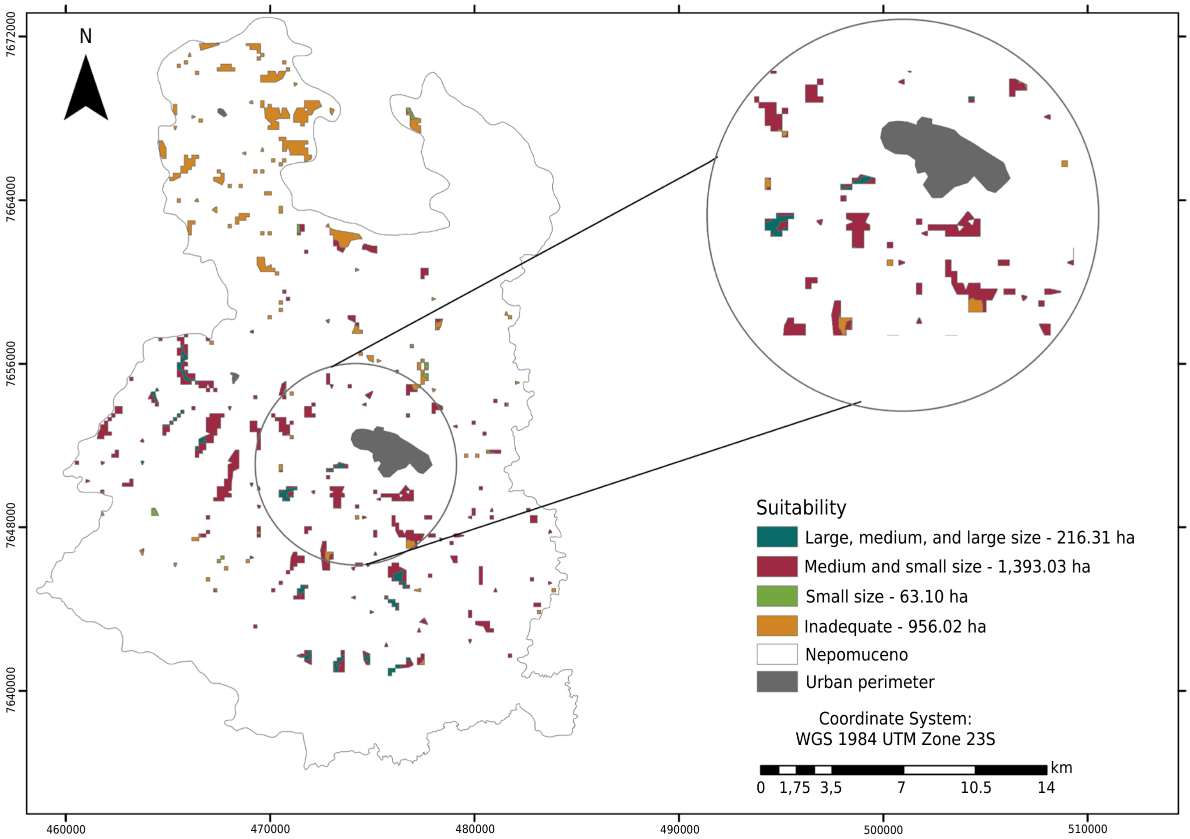

Figure 3. Map of suitability for solid waste disposal from civil construction for Nepomuceno.

Most of the areas for solid waste disposal from civil construction were classified as medium and small (1393.03 ha), where the determining and limiting attribute was the undulated relief where *Latossolos Vermelhos Distróficos* (Acrudox) and *Latossolos Vermelho-Amarelos Distróficos* (Hapludox) predominated. Areas classified as inadequate (956.02 ha) were limited by their location in floodplain soils, where flood risk was the limiting factor, and by the occurrence of *Cambissolos Háplicos Tb Distróficos* (Dystrustept) in undulated relief (Table 4). Notably, although the legislation considers only the distance from water bodies (500 m) for water disposal, this distance was not enough to exclude all floodplain areas as indicated in the soil mapping. This fact highlights the importance of soil surveys on a more detailed scale for the accurate choice of disposal facilities since floodplain environments tend to occur in smaller mapping units.

Areas classified as large, medium, and small (total of 216 ha) were those in an undulated relief with a predominance of *Latossolos Vermelhos Distróficos* (Acrudox), strongly drained soils with a granular structure in the B horizon, which in turn are very weathered-leached and thick. Those are the areas with the most favorable attributes to receive greater volumes of waste daily. Finally, areas classified as small (63.10 ha) were limited by undulated relief.

Normative Copam No. 244 of 2022, which revoked Copam No. 118/2008, is the only one with aspects that surrogates applied pedological information or environmental characteristics. It establishes that waste disposal must be at a minimum distance of 500 m from water bodies in slopes lesser than 30 % and prioritize soils with reduced water permeability. Based on insights promoted by the field campaign and mapping of the study case, as well as accumulated pedological knowledge, the simplicity of normative resolution might lead to potential environmental risks, which are worth noting:

a) Concerning the distance of 500 m from water bodies: floodplains present a complex hydrological dynamic of the extent of inundations during flood events, representing a risk considering only a fixed distance. In this sense, Mello and Curi (2012) suggest applications of pedological and geomorphological indicators as a step forward for hydrological phenomena interpretations.

b) Concerning soils that occur in slopes lesser than 30 %: considering the technical soil survey reports (IBGE, 2015), a broad range of slopes might contain landscapes with different risks of soil erosion. Thus, more specific slope ranges (relief phases, IBGE, 2015) would accurately guide the choice of lands suited for waste disposal facilities. In addition, landscape information should be combined and analyzed, including soil properties such as accumulation of clay content in depth, shallow depths, or greater silt/clay contents, since all of them also increase erosion susceptibility (Resende et al., 2014). Besides the environmental risks, once installed, erosional processes might decrease waste disposal facilities longevity and can increase additional costs of their adequacy.

Table 4. Soil mapping units and their respective suitability for civil construction of waste disposal in m^3 day^{-1}, geographical expression, and the most limiting factors.

Soil mapping unit	Suitability	Area	Most limiting factor
	m^3 day^{-1}	%	
ARGISSOLO VERMELHO Distrófico (Rhodudult) undulated relief	Medium and small size	0.45	Relief
ARGISSOLO VERMELHO – AMARELO Distrófico (Hapludult) strongly undulated relief	Inadequate	0.25	Relief
CAMBISSOLO HÁPLICO Tb Distróficos (Dystrustept) - strongly undulated relief	Inadequate	2.05	Depth
CAMBISSOLO HÁPLICO Tb Distróficos (Dystrustept) - undulated relief	Inadequate	9.37	Depth
CAMBISSOLO HÁPLICO Tb Distróficos (Dystrustept) – gently undulated relief	Inadequate	0.05	Depth
LATOSSOLO AMARELO Distrófico (Hapludox) – undulated relief	Medium and small size	0.29	Relief
LATOSSOLO VERMELHO – AMARELO Distrófico (Hapludox) – strongly undulated relief	Inadequate	7.13	Relief
LATOSSOLO VERMELHO – AMARELO Distrófico (Hapludox) – undulated relief	Small size	2.56	Relief
LATOSSOLO VERMELHO Distrófico (Hapludox) – strongly undulated relief	Small size	0.88	Relief
LATOSSOLO VERMELHO Distrófico (Acrudox) – undulated relief	Medium and small size	65.03	Relief
LATOSSOLO VERMELHO Distrófico (Acrudox) – gently undulated relief	Large, medium and large size	2.82	Unrestricted
LATOSSOLO VERMELHO Distrófico (Acrudox) – flat relief	Large, medium and large size	0.20	Unrestricted
Floodplain soils complex	Inadequate	8.93	Flood risk

c) Concerning soils with lower water permeability: these soils present water flowing less efficiently through the soil pores. Considering this soil property only, soils with high and low suitability for waste disposal are also included (Oliveira et al., 2016; Streck et al., 2018). One example is that instead of only preventing contaminated water from reaching the water table or aquifer, the water stagnation or accumulation - an undesirable attribute for waste disposal sites – increases the risk of contamination of water resources. Thus, for an adequate diagnosis, other soil properties, such as redoximorphic soil colors and the occurrence of perched water tables, must improve soil drainage and permeability diagnosis.

Waste displacement is often considered costly for waste disposal in appropriate locations (Doussoulin and Bittencourt, 2022). In this sense, figure 3 highlights the urban perimeter surrounded mostly by areas classified as having the potential to receive medium and small-sized volumes. This fact, along with proper roads observed during the field campaigns, might reduce the costs of transportation as well as building disposal facilities. Once waste disposal has begun, future assessments are necessary to ensure the sustainability of the system from the maintenance of crucial soil functions, especially those concerning water purification and soil contaminant reduction. Due to the absence of technical guides, diagnostic qualifiers proposed by Costa et al. (2019) are suggested.

CONCLUSIONS

Digital soil map of the municipality of Nepomuceno supported the evaluation of the areas concerning the suitability system proposed. Steep relief and shallow soils were the most determining limitations in reducing the potential size of the areas in this case study. The attributes proposed as criteria for classifying the suitability of areas for solid waste disposal from civil construction complemented the current legislation. In addition, more subsidies were offered to indicate the potential areas in the municipalities' integrated solid waste management plans. This approach may be used under similar environmental conditions as in this study for the southeastern region of Brazil. The suitability to receive medium- and small-sized volumes, combined with the proximity to the urban center and good-quality roads, enables the Nepomuceno municipality to have the potential to allocate landfills in areas that add up to 236 ha.

ACKNOWLEDGMENTS

Our thanks to National Council for Scientific and Technological Development - CNPq and Coordination of Superior Level Staff Improvement - CAPES for the scholarship financing; Regional Consortium of Basic Sanitation – CONSANE for the technical and financial support; Minas Gerais Economic Development Company - CODEMIG for providing the airborne gamma-ray spectroscopy survey information.

AUTHOR CONTRIBUTIONS

Conceptualization: Bruno Silva Villela (supporting), Daniela de Fátima Pedroso (supporting), Iris Helena Antunes Naim (lead), Ivan Massimo Pereira Leite (lead), Luana Sousa Costa (lead), Michele Duarte de Menezes (lead) and Nilton Curi (lead).

Data curation: Bruno Silva Villela (supporting), Daniela de Fátima Pedroso (supporting), Luana Sousa Costa (lead), Marcelo Henrique Procópio Pelegrino (supporting), Maria Eduarda Carvalho Monteiro (supporting), Michele Duarte de Menezes (lead) and Raísa Brito Vilela (supporting).

Formal analysis: Luana Sousa Costa (equal), Michele Duarte de Menezes (lead) and Raísa Brito Vilela (supporting).

Funding acquisition: Daniela de Fátima Pedroso (equal), Ivan Massimo Pereira Leite (equal) and Michele Duarte de Menezes (equal).

Investigation: Daniela de Fátima Pedroso (supporting), Iris Helena Antunes Naim (lead), Luana Sousa Costa (lead), Marcelo Henrique Procópio Pelegrino (supporting) and Michele Duarte de Menezes (lead).

Methodology: Bruno Montoani Silva (supporting), Bruno Silva Villela (supporting), Daniela de Fátima Pedroso (supporting), Iris Helena Antunes Naim (lead), Ivan Massimo Pereira Leite (supporting), Luana Sousa Costa (lead), Marcelo Henrique Procópio Pelegrino (supporting), Maria Eduarda Carvalho Monteiro (supporting), Michele Duarte de Menezes (lead), Nilton Curi (lead) and Raísa Brito Vilela (supporting).

Project administration: Michele Duarte de Menezes (lead).

Resources: Ivan Massimo Pereira Leite (equal) and Michele Duarte de Menezes (equal).

Software: Luana Sousa Costa (lead) and Raísa Brito Vilela (supporting).

Supervision: Michele Duarte de Menezes (lead) and Nilton Curi (supporting).

Validation: Luana Sousa Costa (lead), Marcelo Henrique Procópio Pelegrino (supporting) and Maria Eduarda Carvalho Monteiro (supporting).

Visualization: Luana Sousa Costa (supporting) and Michele Duarte de Menezes (lead).

Writing – original draft: Luana Sousa Costa (equal) and Michele Duarte de Menezes (equal).

Writing – review & editing: Bruno Montoani Silva (supporting), Luana Sousa Costa (equal), Michele Duarte de Menezes (equal) and Nilton Curi (lead).

REFERENCES

Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais - Abrelpe. Panorama dos resíduos sólidos no Brasil 2018/2019. São Paulo: Abrelpe; 2019. Available from: http://abrelpe.org.br/panorama/.

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JDM, Sparovek G. Köppen's climate classification map for Brazil. Meteorol Z. 2013;22:711-28. https://doi.org/10.1127/0941-2948/2013/0507

Amaral FCS. Sistema brasileiro de classificação de terras para irrigação: Enfoque na região semiárida. Rio de Janeiro: Embrapa Solos; 2011.

Andrade JDA, Augusto F, Jardim ICSF. Biorremediação de solos contaminados por petróleo e seus derivados. Eclet Quim. 2010;35:17-43. https://doi.org/10.1590/S0100-46702010000300002

Brasil. Lei nº 12.305, de 2 de agosto de 2010: Institui a Política Nacional de Resíduos Sólidos; altera a Lei no 9.605, de 12 de fevereiro de 1998; e dá outras providências. Brasília, DF: Diário Oficial da União; 2010. Available from: https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm.

Breiman L. Random forests. Mach Learn. 2001;45:5-32. https://doi.org/10.1023/A:1010933404324

Carvalho Junior W, Pereira NR, Fernandes Filho EI, Calderano Filho B, Pinheiro HSK, Chagas CS, Bhering SB, Pereira VR, Lawall S. Sample design effects on soil unit prediction with machine:

randomness, uncertainty, and majority map. Rev Bras Cienc Solo. 2020;44:e0190120. https://doi.org/10.36783/18069657rbcs20190120

Conrad O, Bechtel B, Bock M, Dietrich H, Fischer E, Gerlitz L, Wehberg J, Wichmann V, Böhner J. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geosci Model Dev. 2015;8:1991-2007. https://doi.org/10.5194/gmd-8-1991-2015

Conselho Estadual de Política Ambiental - Copam. Deliberação Normativa Copam nº 118, 27 de julho de 2008: Altera os artigos 2º, 3º e 4º da Deliberação Normativa 52/2001, estabelece novas diretrizes para adequação da disposição final de resíduos sólidos urbanos no Estado, e dá outras providências. Diário do Executivo – Minas Gerais; 2008. Available from: http://www.siam.mg.gov.br/sla/download.pdf?idNorma=7976

Conselho Estadual de Política Ambiental - Copam. Deliberação Normativa Copam nº 217, 6 de dezembro de 2017: Estabelece critérios para classificação, segundo o porte e potencial poluidor, bem como os critérios locacionais a serem utilizados para definição das modalidades de licenciamento ambiental de empreendimentos e atividades utilizadores de recursos ambientais no Estado de Minas Gerais e dá outras providências. Belo Horizonte: Diário do Executivo – Minas Gerais; 2017. Available from: http://jornal.iof.mg.gov.br/xmlui/handle/123456789/192323

Conselho Estadual de Política Ambiental - Copam. Deliberação Normativa Copam nº 244, 27 de janeiro de 2022: Dispõe sobre os critérios para implantação e operação de aterros sanitários em Minas Gerais e dá outras providências. Belo Horizonte: Diário do Executivo – Minas Gerais; 2017. Available from: https://www.jornalminasgerais.mg.gov.br/?dataJornal=2022-02-17

Costa AM, Curi N, Araújo EF, Marques JJ, Menezes MD. Management units for Eucalyptus cultivation in four physiographical regions of Rio Grande do Sul, Brazil. Sci For. 2009;37:465-73.

Costa JR, Pedron FA, Dalmolin RSD, Schenato RB. Field description and identification of diagnostic qualifiers for urban soils in Brazil. Rev Bras Cienc Solo. 2019;43:e0180121. https://doi.org/10.1590/18069657rbcs20180121

Curi N, Silva E, Gomes FH, Menezes MD, Silva SHG, Teixeira AFS. Mapeamento de solos, aptidão agrícola e taxa de adequação do uso das terras do município de Lavras (MG). Lavras: Editora UFLA; 2020.

Doussoulin JP, Bittencourt M. How effective is the construction sector in promoting the circular economy in Brazil and France?: A waste input-output analysis. Struct Change Econ D. 2022;60:47-58. https://doi.org/10.1016/j.strueco.2021.10.009

Ferreira MM, Fernandes B, Curi N. Influência da mineralogia da fração argila nas propriedades físicas de Latossolos da região Sudeste do Brasil. Rev Bras Cienc Solo. 1999;23:515-24. https://doi.org/10.1590/S0100-06831999000300004

Fick SE, Hijmans RJ. WorldClim 2: New 1km spatial resolution climate surfaces for global land areas. Int J Climatol. 2017;37:4302-15. https://doi.org/10.1002/joc.5086

Gee GW, Bauder JW. Particle-size analysis. In: Klute A, editor. Methods of soil analysis: Part 1 Physical and mineralogical methods. Madison: SSSA; 1986. p. 383-411.

Ghosh S, Nanda S. Site suitability analysis for solid waste management using multi criteria analysis. In: Prashanthi M, Sundaram R, editors. Integrated waste management in India. Cham: Springer; 2016. https://doi.org/10.1007/978-3-319-27228-3_3

Gomes LC, Faria RM, Souza E, Veloso GV, Schaefer CEGR, Fernandes Filho EI. Modeling and mapping soil organic carbon stocks in Brazil. Geoderma. 2019;340:337-50. https://doi.org/10.1016/j.geoderma.2019.01.007

Heung B, Bulmer CE, Schmidt MG. Predictive soil parent material mapping at a regional-scale: A Random Forest approach. Geoderma. 2014;214-215:141-54. https://doi.org/10.1016/j.geoderma.2013.09.016

International Atomic Energy Agency - IAEA. Guidelines for radioelement mapping using gamma-ray spectrometry data. Austria: IAEA; 2003. Available from: https://www-pub.iaea.org/MTCD/Publications/PDF/te_1363_web.pdf

Instituto Brasileiro de Geografia e Estatística - IBGE. Manual técnico de pedologia. 3. ed. Rio de Janeiro: Fundação IBGE; 2015. Available from: https://agenciadenoticias.ibge.gov.br/media/com_mediaibge/arquivos/18acacacfd63204b29c6d820a430b8e4.pdf.

Instituto Brasileiro de Geografia e Estatística - IBGE. Pesquisa Nacional de Área da unidade territorial: Área territorial brasileira. Rio de Janeiro: IBGE; 2020. Available from: https://cidades.ibge.gov.br/brasil/mg/nepomuceno/panorama.

Jamil M, Ahmed R, Sajjad H. Land suitability assessment for sugarcane cultivation in Bijnor district, India using geographic information system and fuzzy analytical hierarchy process. GeoJournal. 2018;83:595-611. https://doi.org/10.1007/s10708-017-9788-5

Jenny H. Factors of soil formation: A system of quantitative pedology. New York: McGraw-Hill; 1941.

Kämpf N, Curi N. Formação e evolução do solo (Pedogênese). In: Ker JC, Curi N, Schaefer CEGR, Torrado PV, editors. Pedologia: Fundamentos. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2012. p. 207-302.

Karpinski LA, Pandolfo A, Reinehr R, Rojas JWJ. Gestão diferenciada de resíduos de construção e demolição: Uma visão abrangente no município de Passo Fundo-RS. Estudos Tecnológicos. 2008;4:69-87.

Koreen M, Richardson M. On the importance of training data sample selection in random forest image classification: A case study in peatland ecosystem mapping. Remote Sens. 2015;7:8489-515. https://doi.org/10.3390/rs70708489

Lacoste M, Lemercier B, Walter C. Regional mapping of soil parent material by machine learning based on point data. Geomorphology. 2011;133:90-9. https://doi.org/10.1016/j.geomorph.2011.06.026

Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics. 1977;33:159-74. https://doi.org/10.2307/2529310

Machado DFT, Silva SHG, Curi N, Menezes MD. Soil type spatial prediction from random forest: Different training datasets, transferability, accuracy and uncertainty assessment. Sci Agric. 2019;76:243-54. https://doi.org/10.1590/1678-992X-2017-0300

McBratney A, Field DJ, Koch A. The dimensions of soil security. Geoderma. 2014;213:203-13. https://doi.org/10.1016/j.geoderma.2013.08.013

McBratney AB, Santos MLM, Minasny B. On digital soil mapping. Geoderma. 2013;117:3–52. https://doi.org/10.1016/S0016-7061(03)00223-4.

Mello CR, Curi N. Hydropedology. Cienc Agrotec. 2012;36-2:137-46. https://doi.org/10.1590/S1413-70542012000200001

Menezes MDD, Curi N, Marques JJ, Mello CRD, Araújo ARD. Levantamento pedológico e sistema de informações geográficas na avaliação do uso das terras em sub-bacia hidrográfica de Minas Gerais. Cienc Agrotec. 2009;33:1544-53. https://doi.org/10.1590/S1413-70542009000600013

Minasny B, McBratney AB. A conditioned Latin hypercube method for sampling in the presence of ancillary information. Comput Geosci. 2006;32:1378-88. https://doi.org/10.1016/j.cageo.2005.12.009

Oliveira JMD, Silva SHG, Menezes MDD, Kämpf N, Curi N. Land suitability for final waste disposal with emphasis on septic systems installation in southern Minas Gerais, Brazil. Cienc Agrotec. 2016;40:37-45. https://doi.org/10.1590/S1413-70542016000100003

Oliveira V, Costa AMR, Azevedo WP, Camargo MN, Olmos J. Pedologia: Levantamento exploratório de solos. In: Projeto Radambrasil. Levantamento de Recursos Naturais V.32: Folhas SF.23/24 Rio de Janeiro/Vitória. Rio de Janeiro; 1983. p. 385-552.

Pedron FA, Dalmolin RSD, Azevedo AC, Poelkin EL, Miguel P. Utilização do sistema de avaliação do potencial de uso urbano das terras no diagnóstico ambiental do município de Santa Maria – RS. Cienc Rural. 2006;36:468-77. https://doi.org/10.1590/S0103-84782006000200017

Pelegrino MHP, Silva SHG, Menezes MDD, Silva ED, Owens PR, Curi, N. Mapping soils in two watersheds using legacy data and extrapolation for similar surrounding areas. Cienc Agrotec. 2016;40:534-46. https://doi.org/10.1590/1413-70542016405011416

Ramalho Filho A, Beeh KJ. Sistema de avaliação da aptidão agrícola das terras. 3. ed. rev. Rio de Janeiro: Embrapa-CNPS; 1995.

Resende M, Curi N, Ker JC, Rezende SB. Mineralogia dos solos brasileiros: Interpretação e aplicações. 2 ed. Lavras: Editora UFLA; 2011.

Resende M, Curi N, Rezende SD, Corrêa GF, Ker JC. Pedologia: Base para distinção de ambientes. 6. ed. rev. amp. Lavras: Editora UFLA; 2014.

Roudier P. Clhs: a R package for conditioned Latin hypercube sampling. Available from: <https://cran.r-project.org/web/packages/clhs/clhs.pdf> 23/03/2021.

Roudier P, Beaudette DE, Hewitt AE. A conditioned Latin hypercube sampling algorithm incorporating operational constraints. In: Minasny B, Malone BP, McBratney AB, editors. Digital soil assessments and beyond. Proceedings of the 5th Global Workshop on Digital Soil Mapping, Sydney, Australia, 10–13. Boca Raton: CRC Press; 2012. p. 227-31.

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.

Santos RD, Santos HG, Ker JC, Anjos LHC, Shimizu SH. Manual de descrição e coleta de solo no campo. 7. ed. rev. ampl. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2015.

Sharififar A, Sarmadian F, Malone BP, Minasny B. Addressing the issue of digital mapping of soil classes with imbalanced class observations. Geoderma. 2019;350:84-92. https://doi.org/10.1016/j.geoderma.2019.05.016

Silva SHG, Owens PR, Silva BM, Oliveira GCD, Menezes, MDD, Pinto LC, Curi N. Evaluation of conditioned latin hypercube sampling as a support for soil mapping and spatial variability of soil properties. Soil Sci Soc Am J. 2015;79:603-11. https://doi.org/10.2136/sssaj2014.07.0299

Silva VA, Curi N, Marques JJG, Carvalho LMT, Santos WJR. Soil maps, field knowledge, forest inventory and ecological-economic zoning as a basis for agricultural suitability of lands in Minas Gerais elaborated in GIS. Cienc Agrotec. 2013;37:538-49. https://doi.org/10.1590/S1413-70542013000600007

Sistema Estadual de Meio Ambiente e Recursos Hídricos - Sisema. Infraestrutura de dados espaciais do sistema estadual de meio ambiente e recursos hídricos - IDE-Sisema. Belo Horizonte: Sisema; 2019. Available from: http://idesisema.meioambiente.mg.gov.br.

Smethurst MA. A software tool to rotate spatial data on the surface of the sphere(Earth) for Geosoft's Oasis Montaj. Norway: NGU Report; 2005.

Staunton J, Williams CD, Morrison L, Henry T, Fleming GT, Gormally MJ. Spatio-temporal distribution of construction and demolition (C&D) waste disposal on wetlands: A case study. Land Use Policy. 2015;49:43-52. https://doi.org/10.1016/j.landusepol.2015.06.023

Stoorvogel JJ, Bakkenes M, Temme AJ, Batjes NH, Brink BJ. S-world: A global soil map for environmental modeling. Land Degrad Dev. 2017;28:22-33. https://doi.org/10.1002/ldr.2656

Streck EV, Kämpf N, Dalmolin RSD, Klamt E, Nascimento PD, Schneider P, Pinto LFS. Solos do Rio Grande do Sul. 3. ed. rev. ampl. Porto Alegre: UFRGS, Emater/RS, Ascar; 2018.

Taghizadeh-Mehrjardi R, Schmidt K, Eftekhari K, Behrens T, Jamshidi M, Davatgar N, Toomanian N, Scholten, T. Synthetic resampling strategies and machine learning for digital soil mapping in Iran. Eur J Soil Sci. 2020;71:352-68. https://doi.org/10.1111/ejss.12893

Taveira LRS, Weindorf DC, Menezes MD, Carvalho TS, Motta PEF, Teixeira AFS, Curi N. Land use capability classification adaptation in low and intermediate technology farming systems: A soil erosion indicator. Soil Use Manage. 2019;37:164-80. https://doi.org/10.1111/sum.12555

Torgal FP, Jalali S. Eco-efficient construction and building materials. London: Springer; 2011.

Trouw RAJ, Paciullo FVP, Ribeiro A, Cherman A, Chrispim S, Maciel RR. Nepomuceno - SF.23-V-D-III, escala 1:100.000: Nota explicativa. Minas Gerais: UFRJ/CPRM; 2007. Available from: https://rigeo.cprm.gov.br/handle/doc/10467.

Universidade Federal de Viçosa – UFV / Fundação Centro Tecnológico de Minas Gerais - CETEC / Universidade Federal de Lavras - UFLA / Fundação Estadual do Meio Ambiente - FEAM. Mapa de solos do Estado de Minas Gerais. Escala 1:650.000. Belo Horizonte: FEAM; 2010. Available from: http://www.feam.br/noticias/1/1355-mapa-de-solos.

Ventura KS, Suquisaqui ABV. Application of SWOT and 5W2H tools for analysis of solid urban waste intermunicipal consortia. Ambient Constr. 2020;20:333-49. https://doi.org/10.1590/s1678-86212020000100378

Villela BS. Proposta de conservação e recuperação da Microbacia do Córrego Sapé, Nepomuceno – MG. Lavras: Universidade Federal de Lavras; 2020.

Viscarra-Rossel RA, Behrens T, Ben-Dor E, Brown DJ, Demattê JAM, Shepherd KD, Shi Z, Stenberg B, Stevens A, Adamchuk V, Aïchi H, Barthès BG, Bartholomeus HM, Bayer AD, Bernoux M, Böttcher K, Brodský L, Du CW, Chappell A, Fouad Y, Genot V, Gomez C, Grunwald S, Gubler A, Guerrero C, Hedley CB, Knadel M, Morrás HJM, Nocita M, Ramirez-Lopez L, Roudier P, Campos EMR, Sanborn P, Sellitto VM, Sudduth KA, Rawlins BG, Walter C, Winowiecki LA, Hong SY, Ji W. A global spectral library to characterize the world's soil. Earth-Sci Rev. 2016;155:198-230. https://doi.org/10.1016/j.earscirev.2016.01.012

Weihermann JD, Ferreira FJF, Cury LF, Silveira CT. Gamma-ray spectrometry of granitic suites of the Paranaguá Terrane, Southern Brazil. J Appl Geophys. 2016;132:38-52. https://doi.org/10.1016/j.jappgeo.2016.06.017

Wadoux AMJC, Minasny B, McBratney AB. Machine learning for digital soil mapping: Applications, challenges and suggested solutions. Earth-Sci Rev. 2020;210:103359. https://doi.org/10.1016/j.earscirev.2020.103359

Wilford J. Weathering intensity index for the Australian continent using airborne gamma-ray spectrometry and digital terrain analysis. Geoderma. 2012;183-184:124-42. https://doi.org/10.1016/j.geoderma.2010.12.022

Wilford J, Minty B. The use of airborne gamma-ray imagery for mapping soils and understanding landscape processes. Dev Soil Sci. 2006;31:207-18. https://doi.org/10.1016/S0166-2481(06)31016-1