Mapping of areas suitable for the application of biosolids in the Quadrilátero Ferrífero region, Minas Gerais, Brazil

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Abstract

The recovery of degraded areas is imperative for the sustainability of mining activities. The main action implemented to improve the chemical, physical and biological conditions of soils, tailings and sterile deposits is the incorporation of organic material. Biosolids (hygienized sewage sludge) are among the organic materials that can be applied. However, considering the health risk they represent, not all areas are suitable for receiving this waste. The present research sought to map the environmental suitability of the Quadrilátero Ferrífero (QF) region to assess the applicability of biosolids. For this purpose, maps were elaborated using restrictive criteria established for the safe application of this residue to the soil by means of the Geographic Information System (GIS), using the ArcGIS software, version 10.2. The established criteria were pedology, topography, hydromorphism, presence of protected areas, soil texture, susceptibility to erosion, proximity to urban areas and their overlaps to obtain the final suitability areas. For the exclusion of areas that presented legal restrictions, the criteria of protected area, areas close to water bodies, urban areas, shallow soils and a slope greater than 45% were used, as established in literature, in CONAMA 498/2020 and in the Forest Law - Federal Law 12,652 of 2012. Of the areas analyzed, 58.5% were suitable for biosolid application, equivalent to 10,858.3 ha of the 18,587 ha studied, indicating the feasibility of biosolids application in part of the QF area to be recovered.

keywords: soil recovery, georeferencing, GIS, degraded areas.

1. Introduction

At the end of the mining activity, it is necessary to recover the exploited areas, and for the natural regeneration capacity of the degraded area, for its physical, chemical and biological recovery, several techniques are used, such as the incorporation of organic materials that improve the characteristics physical, chemical and physical-chemical properties of the soil and improves its structure (Baldotto and Baldotto, 2018). Because it contains significant levels of organic matter and nutrients, the biosolid produced after hygienization of sewage sludge, if applied to the soil, becomes a promising technique for the recovery of degraded areas (Gonzaga *et al.*, 2018). This waste, as well as its destination and reuse, is notable for its high generation rate, with approximately 185 thousand tons produced per year in Brazil; 1 million m^3 yr^{-1} in the UK; 4.2 million m^3 yr^{-1} in Switzerland; 50 million m^3 yr^{-1} in Germany and 190,000 tons yr^{-1} in Australia (Moreira *et al.*, 2019).

The multiple, continuous and economic use of natural resources requires a careful analysis of these environmental resources in order to achieve a balance between preserving the environment and production activities, since the intensive and uninterrupted use of soil without conservation techniques can cause serious impacts on the environment and jeopardize soil productivity (Silva *et al.*, 2019). Therefore, it is extremely important to perform studies on the soil conditions, so that its resources are used correctly because the assessment of its suitability permits the identification of the productive potential, and offers important subsidies for planning its sustainable use and management (Silva Neto *et al.*, 2018).

The definition of techniques for identifying suitable areas, based on soil information and climate characteristics, makes it possible to define agroecologically favorable environments and contributes to reducing the risks of environmental degradation. Several methodologies can be used to assess this suitability, including the Land Use Capacity Classification System (Lepsch *et al.*, 1991) and the Land Aptitude Assessment System (Ramalho Filho and Beek, 1995; Schneider *et al.*, 2007).

Selection of the most suitable areas to receive biosolids from a sanitary sewage treatment plant and the consequent benefit is a great challenge, and for that purpose geoprocessing and remote sensing techniques represent powerful tools for verifying the suitability of the soil and the use of natural resources via analyses of soil evaluation, interpretation and classification data, which also ensures the efficient use of natural resources (Fujaco *et al*., 2016; Durães *et al*., 2016). Among the tools used, those based on Geographic Information Systems (GIS) are outstanding (Nascimento and Silva, 2014).

GIS consists of systems that perform computational processing of geographic data and retrieve information, not only based on their alphanumeric characteristics, but also via spatial location (Silva, 2018). With this tool, inventories can be produced to support the planning process, since they make the physical definition of the space feasible. They also offer the possibility of carrying out quantitative and even qualitative analyses of the information on the factors of interest, assigning weights to them and then placing them in an established range of values.

The criteria used for this geospatialization must be determined by the operator based on the legal norms and the databases available for the analyzed location. These criteria include the classification of local topography, the soil type, the presence of water bodies, susceptibility to erosion, the presence of urban areas, the presence of protected areas and permanent preservation areas (PPA) and others (Guimarães, 2018).

Using the Land Use Capacity Classification System and the Agricultural Land Aptitude Assessment System, this study sought to elaborate an environmental suitability mapping of areas with a focus on the application of biosolids, verifying the occurrence of more sensitive regions in which the application is restricted or even prohibited. This research is justified by the high number of degraded areas in the State of Minas Gerais, part of them related to mining processes, in which the recovery process is closely linked to the restoration of their physical and chemical conditions through the application to the soils of organic matter found abundantly in sewage sludge, thereby avoiding its disposal in landfills. Furthermore, it seeks to fill the existing gap in Brazil of studies that verify the environmental feasibility of applying biosolids for the recovery of degraded areas with due analysis of the various environmental aspects.

2. Materials and methods

The present study involved the georeferencing of areas belonging to Mineradora Vale S.A., located in 26 iron ore mines in the Quadrilátero Ferrífero (QF) region in MG, Brazil, in a total of 18,500 ha located in the municipalities of Nova Lima, Itabirito, Brumadinho, Mariana, Ouro Preto, Itabira, Catas Altas, Barão de Cocais, Rio Piracicaba, São Gonçalo do Rio Abaixo, Mario Campos, Belo Vale, Santa Barbara and Congonhas. For its development, a work execution schedule was established, comprised of the following steps:

- Step 1 – Literature review to determine the methodology used and acquire thematic map shapes.
- Step 2 – Organization and preparation of base maps determined as a function of restriction criteria.
- Step 3 – Exclusion of areas with legal restrictions and classification of areas according to the established environmental criteria.
- Step 4 – Interpretation of the obtained maps and preparation of the final soil suitability map.

The methodology used as a reference was that suggested by Souza *et al*. (2008) and maps were obtained using the ArcGIS software, version 10.2, in the GIS environment, with a database scale of 1:450,000.

For selection of the areas, according to their suitability to receive the biosolid, this study based itself on the definition of suitability classes and determination of restriction criteria proposed by Souza *et al*. (2008), on CONAMA 498/2020 and on the availability of a database for Minas Gerais, all of which are presented in Table 1. From the databases used, maps were created for each criterion and they were overlapped to enable the classification of areas that could potentially receive the biosolid.

Table 1 - Restriction criteria applied in the study and databases used for the elaboration of restriction criteria maps for the application of biosolids to the soil.

Restriction criteria	Database
Pedology [1]	Ministério de Meio Ambiente, 2016
Relief[2]	Shuttle Radar Topography Mission - SRTM, 2009
Hydrography [3]	Companhia de Desenvolvimento Econômico de Minas Gerais - CODEMIG, 2011
Hydromorphism [4]	Ministério do Meio Ambiente, 2016
Presence of Protected Areas	Instituto Estadual de Florestas – IEF, 2016
Soil texture	FEAM; UFV, 2010
Susceptibility to erosion	FEAM; UFV, 2010
Proximity to urban areas	SisCom – IBAMA, 2010
Boundaries of degraded areas	Vale, 2016.

1.Soil type; 2. Soil slope; 3. Presence of water bodies; 4. Poorly drained soils

Areas that presented legal restrictions were excluded, and for that, the criteria of presence and proximity to protected areas, water bodies and urban areas were used, as well as the occurrence of shallow soils with a slope greater than 45%, as established in literature and the Forest Law - Federal Law 12.652 of 2012. Based on that, the presence of protected areas or permanent preservation areas and distances of less than 100 m from water bodies and urban areas (shallow wells and residences, public domain roads and interceptor drains and watersheds) were considered to be exclusion factors.

To elaborate the final map, five restriction classes for biosolids use in soils and the criteria for classification of soil suitability as established by Souza *et al*. (2008), were considered. The criteria are presented in Tables 2 and 3, respectively.

Table 2 - Soil classes for the use of biosolids.

Class	Definition
Class I	Soils that present a high potential for biosolid application;
Class II	Despite the high potential for application of biosolids to these soils, it is recommended to assess the need for conservation practices prior to application of the residue;
Class III	Soils with moderate potential for the use of biosolids, soil conservation practices are recommended for the application of this residue;
Class IV	Soils with low potential for the application of biosolids. Mitigating criteria and more specific studies must be presented for the different scenarios, with management alternatives and cultural practices. If protective measures are not effectively taken, there is a risk;
Class V	The application of biosolids is forbidden. There is a risk to the environment and human health in the case of their application to the soil.

Table 3 - Criteria for classification of soil suitability, with regard to the application of biosolids.

Factor	Criteria	Degree	Class
Depth	Latosols or deep argisols	Nil	**I**
	Shallow cambisols or argisols	Moderate	**III**
	Litholic neosols or other areas of shallow soils	Very strong	**V**
Texture	Clayey texture (35-60% clay)	Nil	**I**
	Very clayey texture (>60% clay)	Light	**II**
	Medium texture (15-35% clay)	Moderate	**III**
	Silty texture (<35% clay and <15% sand)	Strong	**IV**
	Sandy texture (<15% sand)	Very strong	**V**
Susceptibility to erosion	Soils in flat relief or clayey latosols in undulating relief	Nil	**I**
	Other soils in slightly undulating relief	Light	**II**
	Soils with medium texture or silty in undulating relief. Soils with silty texture in undulating relief.	Moderate	**III**
	Soils with medium or sandy texture and/or undulating relief. Very clayey soils with hilly relief	Strong	**IV**
	Soils with medium texture in hilly relief. Mountainous or rugged relief regardless of textural class	Very strong	**V**
Protected area	No protected area	Nil	**I**
	Protected area	Very strong	**V**
Relief	Flat relief (0-3%)	Nil	**I**
	slightly undulating relief (3-8%)	Light	**II**
	undulating relief (8-20%)	Moderate	**III**
	hilly relief (20-45%)	Strong	**IV**
	Mountainous or rugged relief (>45%)	Very strong	**V**
Hydromorphism	No indication	Nil	**I**
	Hydromorphic	Very strong	**V**
Hydrography	Areas with water bodies more than 100 m away	Nil	**I**
	Presence of waterbodies within 100 m	Very strong	**V**
Urban areas	More than 100 m from urban areas	Nil	**I**

Source: Adopted from Souza *et al.* (2008).

3. Results and discussion

Soil depth is intimately linked to the possibility of pollutant percolation and groundwater contamination, i.e., the deeper the soil the lower the risk of contamination caused by fertilizer application on its surface, and therefore the restriction imposed on biosolids application are fewer. With georeferencing and the overlapping of maps obtained for the pedology criterion, four main soil classes were identified in which the depth is not restricted: Red-Yellow Argisol, Red-Yellow Latosol, Haplastic Cambisol and Red Latosol, with the last two corresponding to more than 65% of the total area analyzed.

The class of Red-Yellow Argisols occupies a small territorial extension and is in relief conditions that vary from undulating to mountainous. The original vegetation consisted of tropical forest and the soil is generally dystrophic in character with very thick profiles, where the B horizon thickness is greater than 200 cm (Chagas *et al.*, 2013). These characteristics indicate that this soil class presents good potential for the application of biosolids, as regards the need for nutrients and the soil depth. Unlike Latosols, the class of Argisols can be quite erodible, mainly due to its textural gradient, i.e., the difference in texture between the superficial and subsurface horizons (Oliveira, 2012).

Cambisols, in turn, have an incipient B horizon underlying the A horizon which is less than 40 cm thick, and they are distinguished by the low degree of pedogenetic development, therefore among the other pedological classifications of the study area, they are the most sensitive to application of any fertilizers, including biosolids (Araújo, 2011). They occur preferentially in regions of higher altitude, which favors runoff during episodes of rain in the fertilizer application period. For this reason, the slope is also a limiting factor, as the application of this residue is prohibited in areas with inclination exceeding 45°. However, even below that angle, it is still necessary to adopt conservation practices that seek the safe application of fertilizers, including biosolids.

Both Red-Yellow and Red Latosols are soils in an advanced stage of pedogenesis, being very evolved and deep, generally presenting thickness greater than two meters and high permeability, and they are commonly well drained (Oliveira, 2012). In the least undulating reliefs, they can be classified as having low susceptibility to erosion. In addition, they are weathered soils with a low natural nutrient reserve for plants which incurs the demand for external fertilizer sources. The biosolid has a high potential for use and in addition to nutrients, provides organic matter to the soil.

The presence of Neosols in the area of study was not identified. In them the application of biosolids would be prohibited due to the shallow soil depth that increases the risk of groundwater contamination.

According to the classification adopted (Tables 2 and 3), the most common classes found for soils in the area of study were I and III, i.e., with zero and moderate restriction, respectively. The degree of no restriction includes the classes of Latosols and deep Argisols which corresponds to 9,918.54 ha or 53.5% of the total area analyzed, as areas suitable for the application of biosolids. For the moderate degree of restriction, the soil classes most commonly present are Cambisols and shallow Argisols, which correspond to 8,623.44 hectares or 46.5% of the total area under study.

Texture is often directly associated with the retention capacity or the risk of pollutant leaching in the soil. Sandy soils have greater hydraulic conductivity and are therefore susceptible to the transport of ions present in the biosolids, so any chemical residue or fertilizer applied on its surface can be leached to lower layers of the profile, reaching groundwater (Corrêa, 2015). On the other hand, very clayey soils that do not have a granular structure hinder the percolation of water through their profile, leading to surface runoff during rainy periods and consequently the transportation of applied biosolid particles to water bodies and lowland areas.

The soil textural classes found in georeferencing of the analyzed areas were classified as clayey (35-60% clay), with zero degree of restriction, in 52.33% of these areas; very clayey texture (> 60% clay), with a slight degree of restriction, in 8.53% of the study area; and medium texture (15-35% clay), with moderate degree of restriction, in 36.78% of the analyzed areas. It should be noted that for georeferencing of the textural classes, only 97% of the studied areas were examined, since the shape file used did not contain any information regarding the textural class in the region of Mariana, MG. No silty or sandy soils were found in the QF areas analyzed.

Soil susceptibility to erosion is directly related to the type of relief and the exposure of its surface and can be influenced by physical characteristics, such as texture and drainability (Matos, 2010); the greater the susceptibility to erosion, the greater the potential for biosolids disposed in the upper layers of the soil to be carried off and eventually reach water bodies (Souza *et al*., 2008). Costa *et al*., (2018) state that the addition of biosolids considerably reduces losses from soil erosion, precisely because of the greater coverage provided. Because the texture and slope aspects are already addressed in other restriction factors, only the structure was considered as limiting in this criterion; soils with a less developed structure are less suitable for the application of biosolids.

The relief and its slope are aspects of fundamental importance in the identification of areas suitable for receiving the residues since they have a direct influence on water runoff and susceptibility to erosion (Souza *et al*., 2008). The greater the slope, the more rigorous the application of biosolids should be due to the potential risk of particles being carried away during rainy episodes. The mapping of areas suitable for biosolids application, based on the terrain slope criterion, showed that 6.9% had no degree of restriction, with up to 3% slope; 15.61% are classified as slightly undulating relief, with 3 to 8% slope; 28.32% have a moderate degree of restriction, with 8 to 20% slope; and 36.65% have slopes between 20 to 44%, totaling 87.5% of areas suitable for application of the biosolids. It is important to emphasize that the relief classifications of undulating and hilly, despite being suitable for receiving the referred residue, require soil conservation measures. It is therefore necessary that a more specific analysis be done, via systemic assessment of the different elements of the landscape, in order to guarantee the environmentally safe application of the biosolid to the soil.

Areas unsuitable for biosolids application totaled 2,318 ha according to the slope criteria, equivalent to 12.5% of the total area studied. These areas have a slope greater than 45° and are considered by the Minas Gerais Forest Law, Law 20.922 / 13, as permanent preservation areas, and therefore the application of biosolids is prohibited.

Hydromorphic or poorly drained soils have a high water content and therefore tend to create anaerobic conditions in the environment, which are undesirable when organic residues, such as biosolids, are applied to the soil. These conditions are favorable for the maintenance of some pathogens in the environment; they often give off bad odors and can also harm the biological degradation of the incorporated organic matter. These soil types are found at the headwaters and banks of rivers and have groundwater very close to the surface, eventually appearing at certain times of the year, and therefore provide a high risk of surface and groundwater contamination. However, these soil classes were not identified in the georeferencing performed in the QF region.

It is noteworthy that before their application, biosolids must be treated and stabilized so that possible pathogenic agents are reduced and that it is possible to inhibit or reduce the putrefaction potential of the material and its capacity to generate bad odors. The most adopted cleaning processes are liming, that is, the inertification by slaked by lime; pasteurization; beta, gamma and solar radiation; exposure of the sludge to high temperatures (thermal drying); aerobic digestion; anaerobic digestion; hyperchlorination; and composting (Kelessidis; Stasinakis, 2012).

The greatest restriction in relation to suitability for the disposal of biosolids in the soil is related to the hydrography criterion, which considers the presence of water bodies within a distance of 100 m. This characteristic was observed in 29.57% of the areas, equivalent to 5.482 ha unsuitable for biosolids application. It is important to reinforce that, due to the scale, there is a possibility that smaller water bodies are not included in the mapping, and it is necessary to refine the evaluation by confirming the conditions in the field.

The presence of Protected Areas, as established by law 9,985 of July 18, 2000, is a locational restriction due to their fundamental environmental importance in protecting biodiversity and natural resources. After georeferencing the area, considering this item, it was apparent that the presence of Protected areas in concomitance with the areas to be recovered by the application of biosolids is very small in the area under study, consisting of only 0.02%, i.e., an area of 3.38 ha located near the Pico mine, in the municipality of Itabirito.

Of the areas to be recovered, about 3.26% are within 100 m of urban areas, with small and scattered intersections in several municipalities. The 605.24 ha of areas considered unsuitable are distributed among Brumadinho, Nova Lima, Congonhas, Ouro Preto, Mariana, Catas Altas, Barão de Cocais, São Gonçalo do Rio Abaixo, Santa Bárbara, Rio Piracicaba and Itabira.

With regard to urbanization, it should be noted that due to the large scale of the map and low detail as a function of the wide coverage area of the data, some residences , especially those more isolated and located in rural areas may not have been included. Therefore, it is extremely important to systematically confirm suitability in the field, to enable the identification of human occupation dynamics as well as their synergy with the other spatial criteria.

The studied mining complexes with the highest percentage of suitable areas are, in ascending order, Minas Centrais (53.73%), followed by Itabiritos (54.08%), Paraopebas (54.95%), Itabira (57.43%), Mariana (68.28%) and Vargem Grande (68.48%). Although the Vargem Grande complex has the highest percentage of suitable areas, the use restriction classes for the biosolid are limited to three and four, and, according to the class control measures described in the methodology for class IV, more specific studies are necessary for the different scenarios, in addition to appropriate management practices during application of the residue. Table 4 shows the results of areas suitable and unfit for the application of biosolids, by suitability class.

From analysis of the data presented it can be observed that about 31.3% of the evaluated areas comprised classes I, II and III, in which care regarding handling and application of the biosolids are less restrictive. Although the areas classified as class IV require special care, as mentioned above, application is permitted.

Table 4 - Quantification of the areas suitable for biosolids application, according to the class and proportion in relation to the total area.

Class	Suitable area (ha)	Total area analyzed (ha)	Proportion in relation to the total area of the basin (%)
I	331.5	18,587	1.8
II	914.5		4.9
III	4,562		24.6
IV	5,050		27.2
V	7,690.3		41.4

The final maps of areas suitable for biosolids application, with analyses of each complex, are shown in Figure 1, Figure 2, Figure 3, Figure 4, Figure 5 and Figure 6.

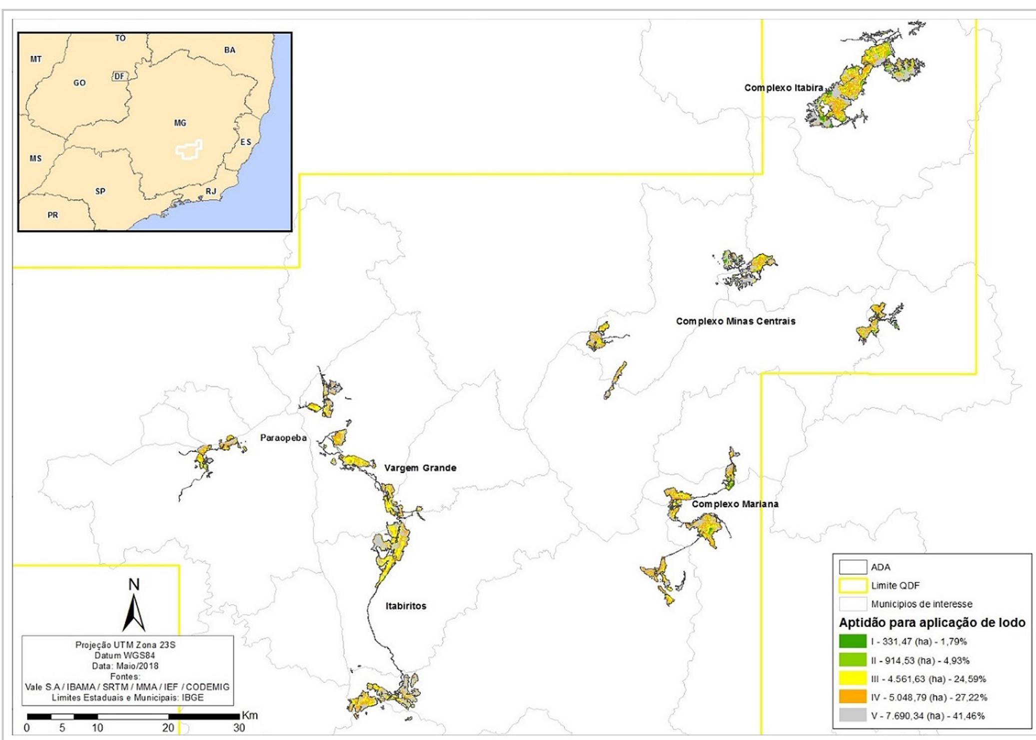

Figure 1 - Map of areas suitable for biosolids application to the soil of the Quadrilátero Ferrífero.

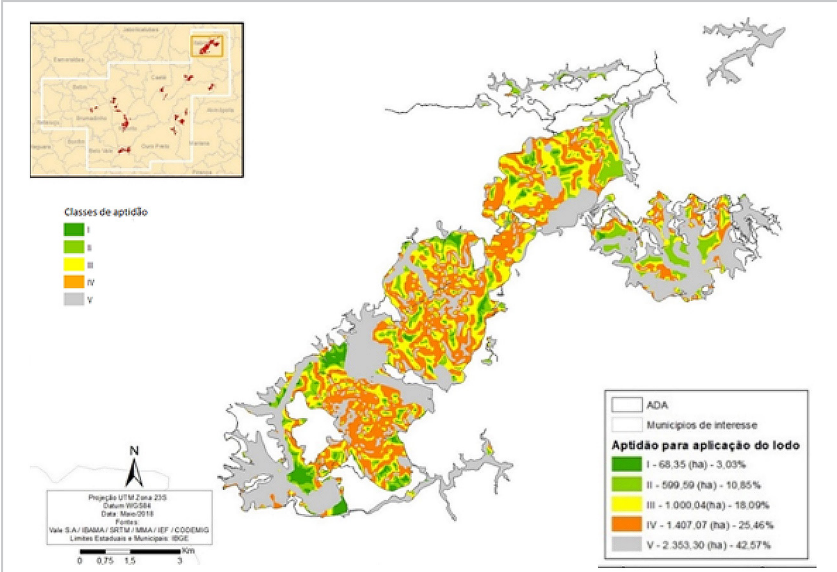

Figure 2 - Map of areas suitable for the application of biosolids in the Itabira Complex.

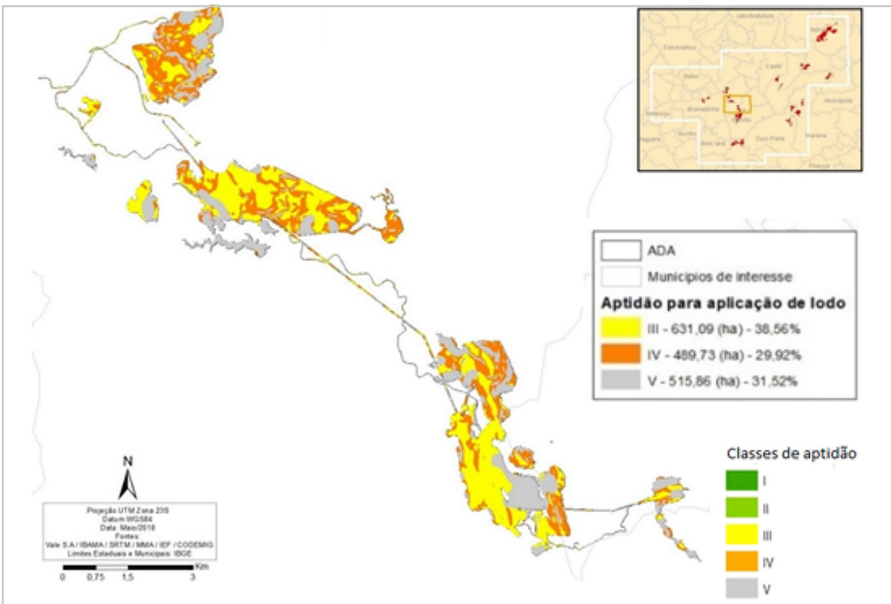

Figure 3 - Map of areas suitable for the application of biosolids in the Vargem Grande Complex.

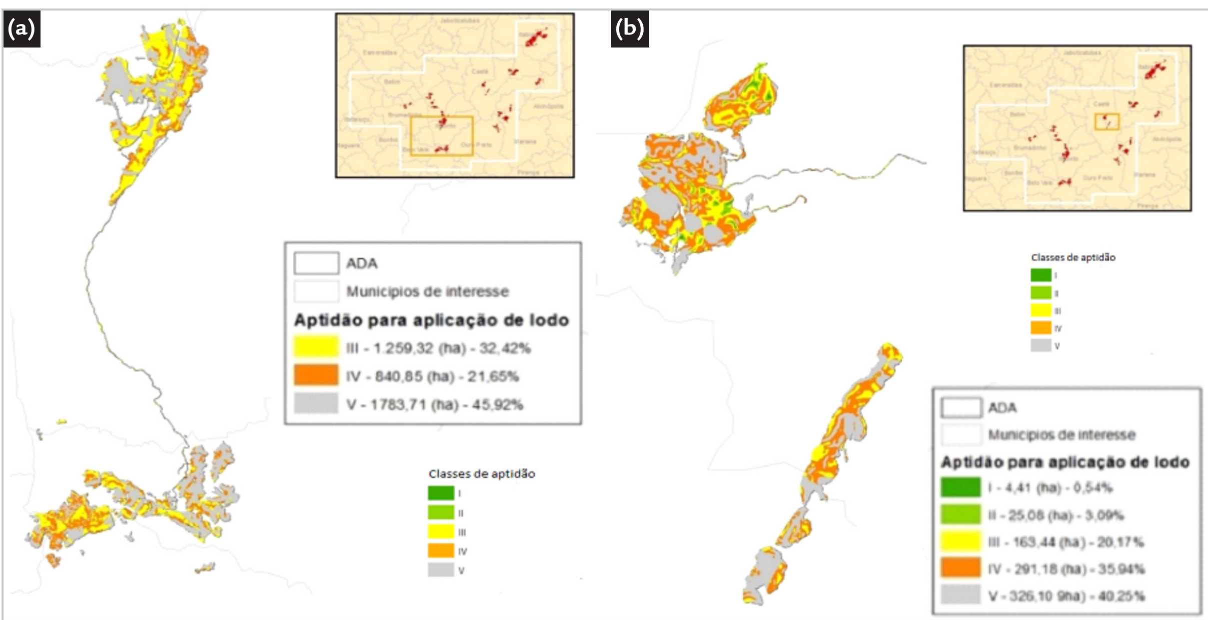

Figure 4 - Map of areas suitable for the application of biosolids in the Itabiritos Complex (a) and Minas Centrais Congo Soco and Baú Complex (b).

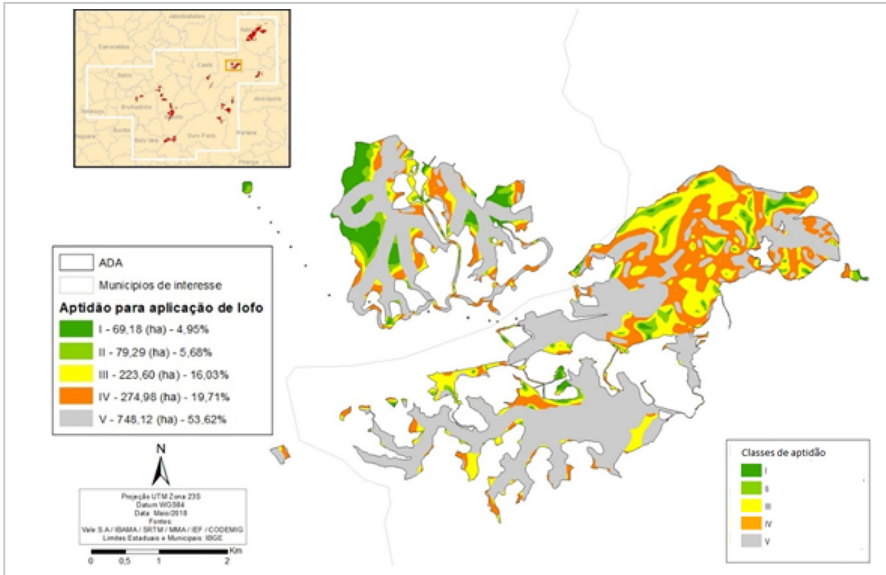

Figure 5 - Map of areas suitable for the application of biosolids in the Brucutu Complex.

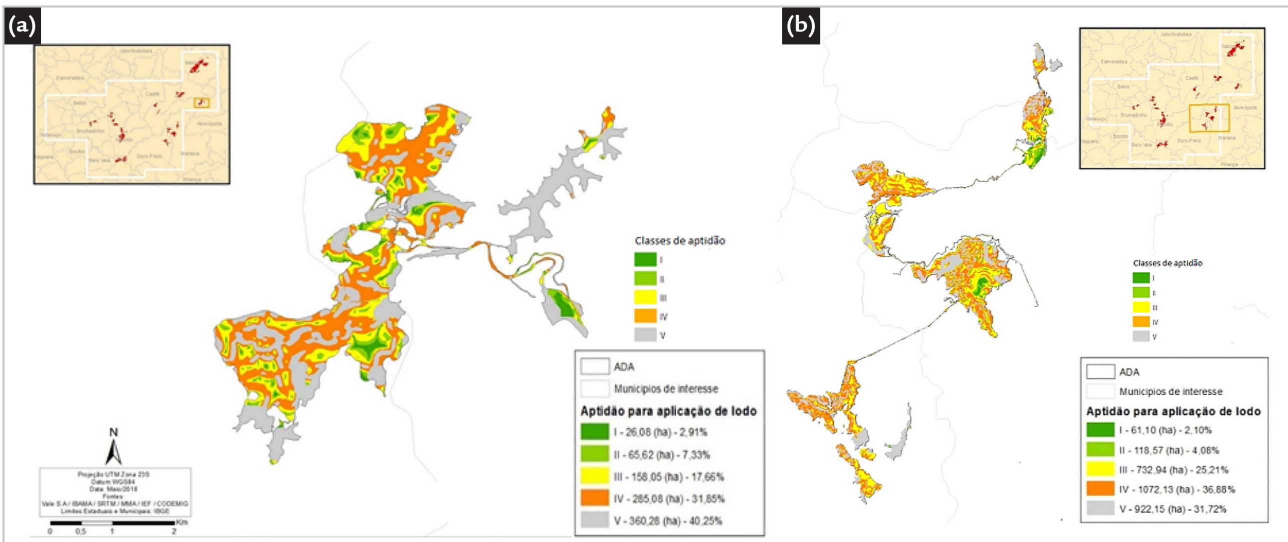

Figure 6 - Map of areas suitable for the application of biosolids in the Minas Centrais Água Limpa Complex (a) and Mariana Complex (b).

4. Conclusion

The establishment of suitability classes based on restrictions to biosolids application and use of the GIS tool enabled the identification of areas that could potentially receive this residue and achieve their environmental recovery. Of a total area of 18,587 ha analyzed in the Quadrilátero Ferrífero region, 58.5% or 10,858.3 ha were environmentally suitable for the application of biosolids, which shows the great potential for disposal of these residues to aid in the recovery of degraded areas located in this iron ore mining region. It is interesting to highlight that the areas classified as class IV have permitted application, however, require special care. Furthermore, it is concluded that the multi-criteria analysis used in the study makes it possible to evaluate and validate the potential for application of biosolids in an environmentally appropriate way, considering that the generation of sewage sludge in the region is about five hundred times smaller than the amount needed to recover the areas.

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