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MECHANIZED WOOD HARVESTING APTITUDE ZONING

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Resumo

Zoneamento de aptidão para colheita mecanizada de madeira. A necessidade de elevar a produtividade dos empreendimentos florestais, criou a necessidade de incrementar o nível de mecanização das atividades. Objetivou-se, com o presente estudo, -avaliar a aptidão das áreas do estado do Espírito Santo à implementação da colheita mecanizada de madeira de, utilizando o sistema de toras curtas. Para a prospecção das áreas aptas à mecanização, foi realizada a álgebra dos mapas de zoneamento edafoclimático do Eucalyptus, uso e ocupação da terra, declividade, unidades de conservação e suas respectivas zonas de amortecimento. Para tal foram definidas as zonas de aptidão com base nas condições edafoclimática para a espécie avaliada, sendo as temperaturas entre 19 e 26ºC, déficit hídrico de 30 a 210 mm e precipitação média anual entre 900 e 1800 mm, definidas como aptas. O uso e ocupação da terra foi classificado como apto, apto com restrição tipo II, apto com restrição tipo III e inapto. Para as classes de aptidão referentes à declividade, foram criadas três categorias: apta (0 – 27º), apta com restrição tipo I (27,1 – 35º) e inaptas (>35º). Os resultados demonstraram que o Estado apresenta 39,45% de toda a sua área apta à implementação de colheita mecanizada de madeira do Eucalyptus e 47,91% inaptas. Com os resultados, os autores concluíram que a microrregião Nordeste se destacou, como a proporção de áreas aptas à mecanização da colheita de Eucalyptus e que a metodologia empregada apresenta potencial de uso e adaptação em outras áreas de estudo do mundo.
Palavras-chave: Operações florestais; geotecnologias; uso e ocupação da terra; modelo digital de elevação; zoneamento edafoclimático

Abstract

The need to increase forest enterprises’ productivity has demanded higher levels of mechanization. The objective of this study was to evaluate the suitability of areas in Espírito Santo State to implement mechanized wood harvesting using a short log system. To prospect suitable areas for mechanization, an algebra map of Eucalyptus edaphoclimatic zoning, land use and occupation, slope, conservation units and their respective buffer zones was performed. Thus, suitability zones were defined based on edaphoclimatic conditions for evaluated species, with temperatures between 19 and 26ºC, water deficit from 30 to 210 mm and annual average rainfall between 900 and 1800 mm defined as suitable. Land use and occupation were classified as fit, fit with type II limitation, fit with type III limitation and unfit. For slope classes, three categories were created: fit (0 - 27º), fit with limitation type I (27.1 - 35º) and unfit (> 35º). Results showed that the State has 39.45% of its entire area able to implement mechanized wood harvesting for Eucalyptus, while 47.91% of it is unfit. Based on the results, the authors concluded that the Northeast micro-region stood out with large, suitable areas for Eucalyptus harvest mechanization and that the employed methodology has potential for use and adaptation in other study areas around the world.
Keywords: Forestry operation; geotechnologies; strategic planning; forest management; eucalyptus.

INTRODUCTION

The pursuit of competitiveness in the demanding timber market has forced forestry companies to use increasingly sophisticated production techniques (FIEDLER *et al.*, 2013; HOLZFEIND *et al.*, 2018; OBI; VISSER, 2017). To ensure survival, these companies need to adopt systems that regulate production, weigh low cost and optimize available resources (LOPES *et al.*, 2016). To achieve these goals, planning tools are indispensable for forestry companies in their production processes (MAGALHÃES; KATZ, 2010). A widespread strategy to increase productivity, standardize production, reduce operating expenses, reduce labor dependency and improve ergonomic conditions is the implementation of mechanized systems along the production process (DINIZ *et al.*, 2018b; VISSER *et al.*, 2014).

Wood harvesting is the stage with the highest mechanization level, due to low labor supply for manual or semi-mechanized systems, hazardousness, need for high productivity and low operating costs. This stage consists of cutting, felling, loading, extracting and unloading, which is responsible for about 50% of the final cost of wood put into the factory (DINIZ *et al.*, 2018a). Among harvesting stages, extraction (displacement of wood from stands interior to roadsides or intermediate courtyards) is considered the most complex due to influence factors, such as slope, soil type, weather conditions, modal used, stand characteristics and extraction distances (DINIZ *et al.*, 2019; LOPES; DINIZ, 2015; SANTOS *et al.*, 2013).

Slope is currently the biggest challenge faced by forest companies, as it requires careful planning and use of specific machines and techniques, which allows for high productivity and low level of environmental degradation, despite their high cost (LOPES; DINIZ, 2015; VISSER *et al.*, 2014). In the Espírito Santo State, there are regions with rugged reliefs, making it difficult to insert large machines for wood harvesting. Among harvesting alternatives in these regions, auxiliary traction winches (ATW) stand out (HOLZFEIND *et al.*, 2018) because they allow flat area machines to perform activities on slopes of up to 27º (LOPES *et al.*, 2016). However, even with the use of equipment such as ATWs, crop productivity on steep terrain cannot outperform flatland, in addition to being a higher-cost operation.

This research was based on the hypothesis that the application of geoprocessing techniques may indicate the areas most susceptible to mechanized eucalyptus forest harvesting in Espírito Santo. Therefore, due to the scarcity of research that focuses on wood harvesting in regions with rugged terrain, which has high associated costs and operational complexity, this study aimed to prospect suitable areas for wood harvesting mechanization by the short-log system in Espírito Santo State, Brazil with emphasis on land slope, land use and occupation, as well as edaphoclimatic zoning for Eucalyptus.

It is also important to highlight that planted forests have been an alternative used by several countries to circumvent the adverse effects caused by exponential deforestation. Deforestation alters the local and global climate, the quality of water and aquatic environments and potentiates the loss of biodiversity, erosive processes, and desertification. Thus, this research, besides having an economic and social appeal, is extremely important for reducing the pressure on native forests and, consequently, reducing illegal deforestation rates.

MATERIALS AND METHODS

Physical aspects of the study area

The study was carried out to the full extent of Espírito Santo state (ES), located in the southeastern region of Brazil, between meridians 39º39'36” and 41º52'12” west longitude of Greenwich and parallels 17º53'24” and 21º18'00” south latitude (Fig. 1).

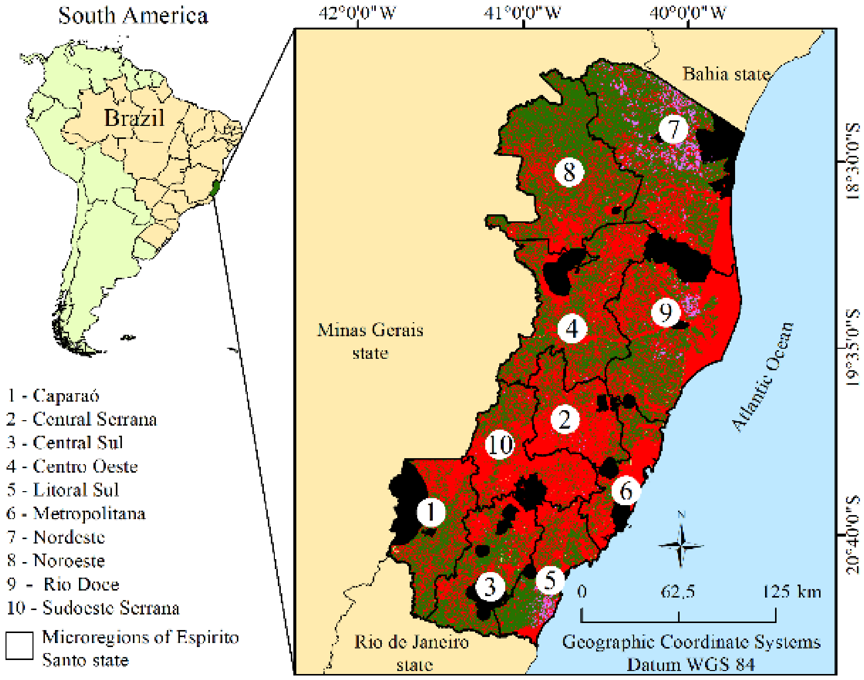

Figure 1. Geographic localization of Espírito Santo State, Brazil.
Figura 1. Localização geográfica do estado do Espírito Santo, Brasil.

The state has a total area of 4,607,444.4 ha (IBGE, 2020), and is subdivided into 10 planning micro-regions, (Caparaó, Central Serrana, Central Sul, Centro Oeste, Litoral Sul, Metropolitana, Nordeste, Noroeste, Rio Doce, and Sudoeste Serrana) according to State Law Nº 9,768 of 2011 (ESPÍRITO SANTO, 2011). According to the Köppen classification, Espírito Santo is into climate zones A and C, the first being hot and humid and the second, tropical altitude. (KOTTEK *et al.*, 2006).

Methodological Steps

The research was developed according to the following methodological steps: 1) Eucalyptus edaphoclimatic zoning; 2) Determination of apt slope classes; 3) Determination of apt land use and occupation classes; 4) Determination of improper areas; 5) Map Combination and Minimum Area Constraint; and 6) Final map elaboration.

Step 1. Eucalyptus edaphoclimatic zoning

For Eucalyptus climatic zoning, a 30-year meteorological data series with 109 rainfall stations located in Espírito Santo state and neighboring states was used. The agroclimatological water balance proposed by Thornthwaite and Mather (1955) was calculated from data. Thus, we proceeded with punctual spatial vectorization of meteorological stations and then applied multiple linear regression, with X and Y (UTM) coordinates as independent variables, and temperature as the dependent one, as shown in Equation 1 and proposed by Sperandio *et al.* (2010).

$$T = \beta_0 + \beta_1 ALT + \beta_2 X + \beta_3 Y \quad (1)$$

Where: T is the temperature (°C), β_0 is the regression constant (dimensionless), β_1, β_2 and β_3 are the regression coefficients for variables (dimensionless), ALT is the altitude (m), X is UTM coordinate X (m) and, Y is UTM coordinate Y (m).

In addition, we have used the Shuttle Radar Topography Mission (SRTM) digital elevation model (MDE), 1: 250,000, made available by Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA). By map algebra, multiple linear regression equations and their respective independent variables were used to generate matrix images of monthly average temperatures and annual average temperatures. Matrix images of rainfall and annual water deficit were generated from kriging spherical interpolation, with adjustment of semivariogram. Then, annual average temperature, rainfall and annual water deficit matrix-images were reclassified to represent aptitude, limitation and disability classes for studied species.

Aptitude classes were based on Sperandio *et al.* (2010) findings, who defined temperature class between 19 and 26ºC, water deficit from 30 to 210 mm and annual average precipitation between 900 and 1800 mm as fit class, and the others as unfit. From soil classes images, made available by Instituto Estadual de Meio Ambiente e Recursos Hídricos (IEMA), an edaphic aptitude reclassification was performed for Eucalyptus, where Argisols, Cambisols, Chernosol, Oxisol, Fluvic Neosol, Litholic Neosol, Red Nitosol and Haplosol were considered as unsuitable. Thus, the Eucalyptus edaphoclimatic fitness map was generated by combining agroclimatic and edaphoclimatic fitness maps.

Step 2. Determination of apt slope classes

For the elaboration of slope classes, a SRTM Digital Elevation Model, with 30 m spatial resolution and UTM datum coordinate system WGS 1984 obtained from Google Earth Engine was used. The slope tool, available in the Spatial analyst tools extension of ArcGis 10.3 software, was used to draw the Espírito Santo State slope map, in degrees. After this procedure, slope categories were reclassified based on the potentialities of mechanized harvesting systems. According to Holzfeind *et al.* (2018), Lopes *et al.* (2016) e Robert *et al.* (2018), 0 to 27º slope class is suitable for the implementation of mechanized wood harvesting without using auxiliary traction winches (ATW), maintaining good productivity. In regions with declivity between 27.1 and 35 °, mechanized harvesting becomes possible with ATW use, which was characterized as a type I limitation. However, in slopes with declivities greater than 35 °, mechanization is not possible.

Step 3. Determination of apt land use and occupation classes

Shapefile extension files containing land use and occupation polygons for the Espírito Santo state, from 2012 to 2015, were obtained from Instituto Estadual de Meio Ambiente e Recursos Hídricos (IEMA). For mapping, IEMA used orthophotos with a 1: 25,000 scale and 25 cm spatial resolution. Land use and occupation within the state were classified according to the following classes of forest cultivation suitability: Able: Exposed soil, reforestation, pasture and macega; Able with limitation type II: Annual agriculture; and Able with limitation type III: Other. Inapt: Native forest; rocky outcrop; buildings; marshes; perennial agriculture; mineral extraction; water bodies; mangrove and sandbank; rupestrian field. In “Type II limitation” regions, it is possible to grow forest species if agronomic crops are replaced by reforestation. However, in type III limitation areas, it is necessary to verify the site’s actual conditions, requiring fieldwork to analyze the possibility of implementing a forest planting, since it is not possible to verify the area's true condition through photointerpretation.

To determine each class's influence on mechanized harvesting implementation within the study area, the area of each class was calculated. In sequence, the polygonal vector file was converted to matrix format for later combination.

Step 4. Determination of improper areas

Based on Conservation Units (CU) management plans provided by Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), a spreadsheet was prepared using Excel 2019 software, containing geographic coordinates of the vertices of CUs boundaries. Subsequently, this information was imported into ArcGis 10.3, where points were converted into polygons in order to make buffer zones of the referred Conservation Units. For CUs that had no data regarding their management plan, a 3km Buffer was applied, as recommended by CONAMA Resolution Nº 428 of 17 of December 2010. Buffer zones of state-protected areas were made available by Instituto Estadual de Meio Ambiente e Recursos Hídricos (IEMA).

Step 5. Map Combination and Minimum Area Constraint

To combine previously generated maps, two different ArcgGis 10.3 tools were used. For the intersection of information between slope, land use and edaphoclimatic zoning, the Combine tool, from Spatial Analyst Tools extension, was applied. This tool combines different raster files so that a unique output value is assigned to each combination of input values. After generating this combination, we applied the Update tool, from Analyst tools extension, to insert improper areas into the combined map, to superimpose values contained in those specific areas. The use of a mechanized short-log harvesting system is not feasible in small areas due to high costs of purchasing its machinery (Harvester and Forwarder). Thus, from previously generated information, an Export Data was performed in apt class (apt, apt with type I limitation, apt with type II limitation, apt with type III limitation). Subsequently, data were reclassified so that areas smaller than 10 hectares (<10 ha) became unfitted for mechanization. Next, the Update tool was used to add the new aptitude classes to the old attribute table.

Step 6. Final map elaboration

Due to differences in relief, climate and temperature that exists in the different regions of the Espírito Santo State, clippings were made in previously generated maps through vector files of the 10 state planning micro-region. Thus, individual maps and tables for each micro-regions were generated, allowing a more detailed and critical analysis. The present study followed a chronological order of execution according to the flowchart presented in Figure 2.

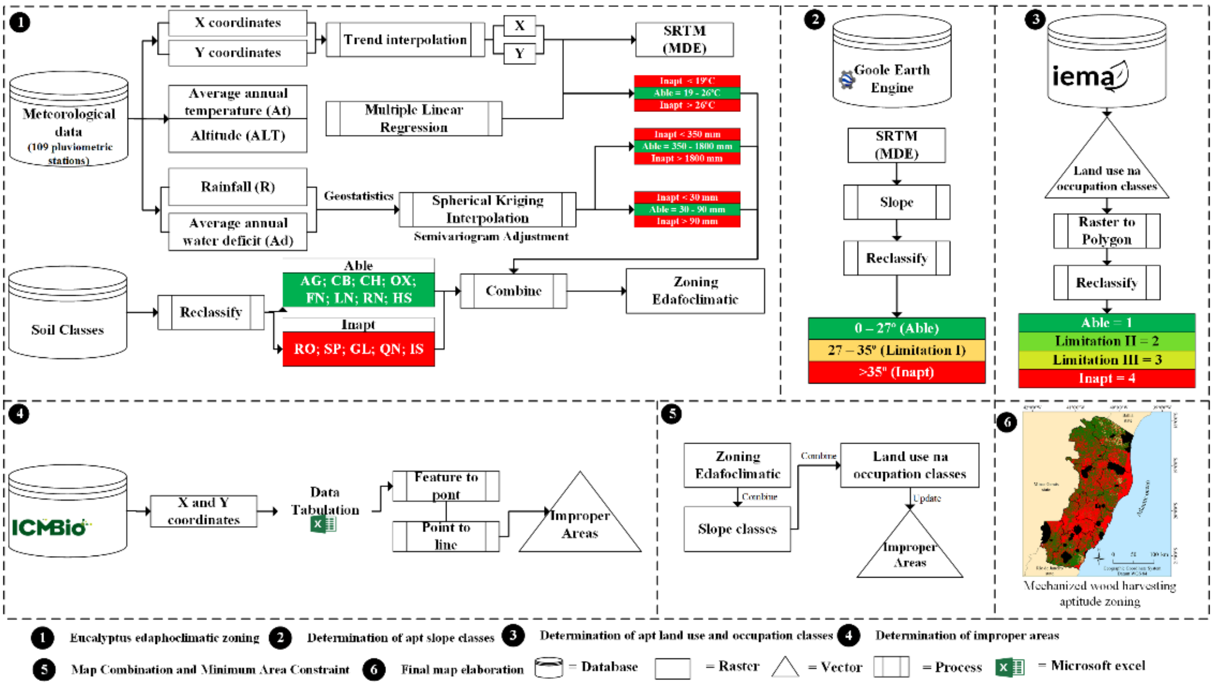

Figure 2. Methodological flow chart with necessary steps to develop the research.
Figura 2. Fluxograma metodológico com os passos necessários para desenvolver a pesquisa.

RESULTS

Edaphoclimatic zoning, slope classes, land use and occupation and improper areas

Figure 3 illustrates results found for Eucalyptus edaphoclimatic zoning, slope, use and occupation classes and improper areas in Espírito Santo State micro-regions.

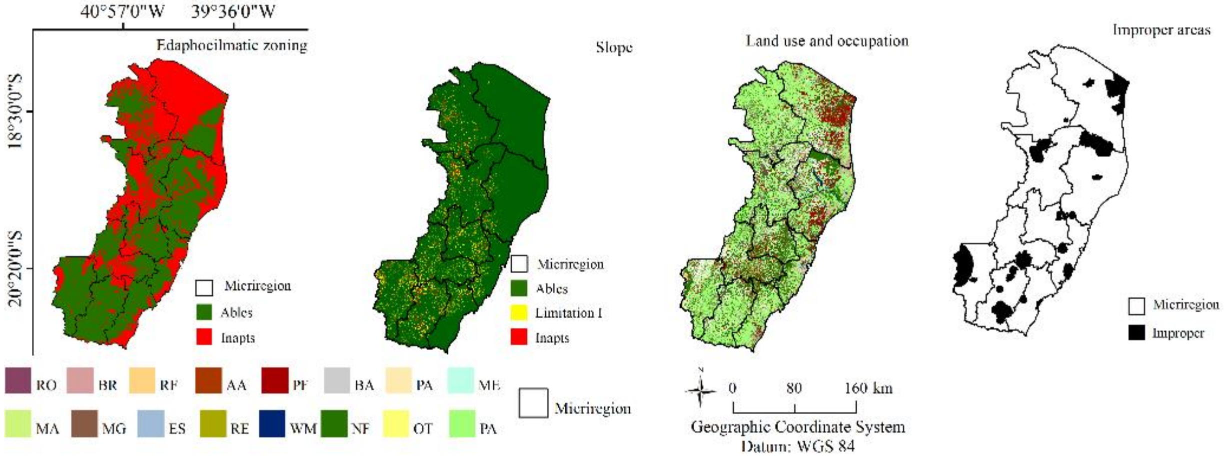

Figure 3. Eucalyptus edaphoclimatic zoning, slope, use and occupation classes and improper areas. Where, AR: Rock Outcrop; AE: Built Area; BR: Swamp; CR: Rupestrian Field; AA: Annual Agriculture; AP: Perennial Agriculture; MS: Mineral Extraction; MA: Macega; MG: Mangrove; MD: Water Mass; MN: Native Forest; OT: Other; PA: Pasture; FP: Planted Forest; RE: Restinga and SE: Exposed Soil.

Figura 3. Onde, AR: Afloramento Rochoso; AE: Área Construída; BR: Pântano; CR: Campo Rupestre; AA: Agricultura Anual; AP: Agricultura Perene; MS: Extração Mineral; MA: Macega; MG: Mangue; MD: Massa de Água; MN: Mata Nativa; TO: Outro; PA: Pastagem; PF: Floresta Plantada; RE: Restinga e SE: Solo exposto.

Table 1. Area, in hectares, by Eucalyptus zoning suitability class, by ES microregion.
Tabela 1. Área, em hectares, por classe de aptidão ao zoneamento do Eucalyptus, por microrregião do ES.

Microregion	Zoning (ha)	
	Apt	Inapt
Caparaó	328,780.02	54,592.20
Central serrana	246,047.05	50,502.37
Central sul	335,682.67	37,588.40
Centro oeste	492,057.68	68,372.48
Litoral sul	229,963.94	48,847.82
Metropolitana	138,008.26	94,524.61
Nordeste	702,123.45	99,204.39
Noroeste	601,817.39	33,279.05
Rio doce	463,071.76	200,735.23
Sudoeste serrana	269,292.05	112,953.58
Total	3,806,844.26	800,600.14

Table 2 presents the classes in each state micro-region.

Table 2. Area, in hectares, by slope suitability class, by ES microregion.
Tabela 2. Área, em hectares, por classe de aptidão à declividade, por microrregião do ES.

Microregion	Slope classes (ha)		
	Apt	Limitation I	Inapt
Caparaó	329,437.14	40,096.72	13,838.35
Central serrana	261,082.11	27,994.27	7,473.05
Central sul	322,170.26	34,714.21	16,386.60
Centro oeste	514,134.00	32,340.05	13,956.11
Litoral sul	258,765.20	15,892.27	4,154.30
Metropolitana	216,674.13	12,207.98	3,650.77
Nordeste	800,045.71	721.20	560.93
Noroeste	591,401.81	26,292.99	17,401.64
Rio doce	648,738.57	11,019.20	4,049.22
Sudoeste serrana	334,388.48	38,683.26	9,173.90
Total	4,276,837.40	239,962.14	90,644.86

Table 3 is related to results from land use and occupation classes of each microregion of the state.

Table 3. Area, in hectares, by suitability class of land use and occupation, by state micro region.
Tabela 3. Área, em hectares, por classe de aptidão ao uso e ocupação da terra, por microrregião.

Microregion	Land use and occupation classes (ha)			
	Apt	Inapt	Limitation II	Limitation III
Caparaó	208,362.80	160,824.65	3,412.01	10,772.76
Central serrana	101,746.11	170,071.09	14,352.99	10,379.23
Central sul	207,911.98	149,719.03	3,247.46	12,392.60
Centro oeste	281,784.28	256,228.67	4,539.48	17,877.72
Litoral sul	160,830.42	93,531.99	15,946.44	8,502.91
Metropolitana	89,339.13	123,079.65	1,744.00	18,370.10
Nordeste	477,784.01	240,133.94	71,070.67	12,339.21
Noroeste	419,735.24	198,785.19	3,111.97	13,464.04
Rio doce	296,854.49	332,235.40	19,980.59	14,736.52
Sudoeste serrana	156,781.48	197,830.55	12,918.61	14,714.99
Total	2,401,129.94	1,922,440.15	150,324.23	133,550.08

Based on Table 1 results, the Nordeste e Noroeste micro-regions stand out for presenting the largest areas suitable for Eucalyptus zoning, representing 7023,23.45 ha and 601,817.39 ha respectively, while the smallest apt area corresponds to the Metropolitana micro-region, with 138,008.26 ha. Regarding Inapt class, Rio Doce microregion has the largest proportion in area, with 200,735.23 ha while the smallest areas are represented by Noroeste (33,279.05 ha) and Central Sul (37,588.4 ha) micro-regions.

Regarding slope suitability classes (Table 2), the largest expressive area for Apt class is represented by the Nordeste micro-region, with 800,045.71 ha while the smallest area is represented by Metropolitana micro-region with 216,674.13 ha. For Apt class with type I limitation, the Caparaó micro-region presented 40,096.72 ha and, the Sudoeste Serrana micro-region, 38,683.26 ha, making them stand out as the most representative areas in extension. The smallest area for this class is represented by the Nordeste micro-region with 721.2 ha. Regarding Inapt class, the largest areas correspond to Noroeste (17,401.6 ha) and Central Sul (16,386.6 ha) micro-regions, and the smallest area is presented by the Nordeste microregion, equivalent to 560.93 ha.

As to aptitude for land use and occupation (Table 3), the largest and smallest extensions of Apt areas correspond to Nordeste (477,784.01 ha) and Metropolitana (89,339.13 ha) micro-regions, respectively. For Inapt class, the Rio Doce micro-region has the largest area with 332,235.40 ha while the smallest one is represented by the Litoral Sul region with 93,531.99 ha. Regarding Apt class with type II limitation, the Nordeste region presented the largest extension in area with 71,070.7 ha, while the Metropolitana region, with 1,744 ha, presented the smallest area. For Apt class with type III limitation, Metropolitana (18,370.1 ha) and Centro Oeste (17,877.72 ha) micro-regions had the highest extensions. The smallest area is represented by the Litoral Sul microregion with 8,502.91 ha.

Final map

The resulting map after intersecting zoning, slope, land use (UOT), improper maps, and limitation of areas larger than 10 ha is shown in Figure 4.

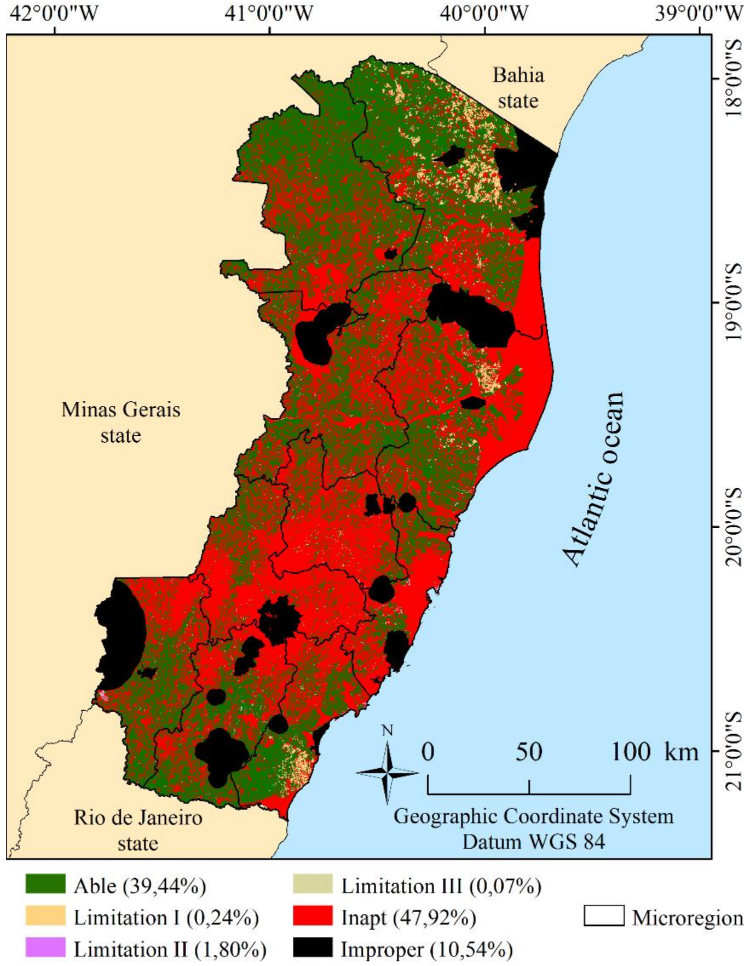

Figure 4. Wood harvesting mechanization classes.
Figura 4. Classes de aptidão à mecanização da colheita de madeira.

Table 4 represents the percentage of aptitude classes for mechanized harvesting, distributed according among micro-regions.

Table 4. Proportion of aptitude classes by microregion.
Tabela 4. Proporção de classes de aptidão por microrregião.

Microregion	Aptitude classes (%)					
	Apta	ALI	ALII	ALIII	Inapt	Improper
Caparaó	137,629.69	899.21	11.22	792.27	149,542.77	94,543.83
Cent. serrana	63,911.68	465.30	1,629.85	88.57	221,134.80	9,479.35
Central sul	142,706.22	1,315.44	229.32	445.26	153,533.20	75,160.24
Centro oeste	232,730.04	1,431.48	821.58	749.01	282,734.57	42,077.27
Litoral sul	122,160.20	780.56	12,072.45	411.62	129,552.42	13,953.20
Metropolitana	50,864.22	1,871.79	172.07	43.24	144,614.13	33,987.76
Nordeste	389,238.02	960.27	55,460.10	0.00	257,506.22	98,263.60
Noroeste	388,277.81	706.29	598.96	101.01	233,504.45	11,968.27
Rio doce	207,413.69	1,711.12	11,353.80	63.84	363,942.60	79,445.71
Sud. serrana	82,490.85	824.84	452.64	376.54	271,465.75	26,772.19
Total	1,817,422.42	10,966.28	82,802	3,071.35	2,207,530.92	485,651.42

Where: ALI = Apt with type I limitation, ALII = Apt with type II limitation, ALIII = Apt with type III limitation.

According to Table 4 results, Nordeste and Noroeste micro-regions stand out for presenting the largest areas suitable for harvest mechanization, representing 389,238.02 ha and 388,277.81 ha respectively, while the smallest Apt area corresponds to the Metropolitana micro-region, with 50,864.22 ha. For Apt class with type I limitation, Metropolitana micro-regions, with 1,871.79 ha and Rio Doce, with 1,711.12 ha, stood out as the most representative areas in extension. The smallest extension area for this class is represented by the Central Serrana micro-region with 465.3ha. Regarding Apt class with type II limitation, the Nordeste region presented the largest area extension, with 55,460.1 ha, while the Caparaó region, with 11.22 ha, presented the smallest proportion in area. For Apt class with limitation type III, the Caparaó (792.27 ha) and Centro Oeste (749.01 ha) micro-regions presented the largest extensions in area while the Nordeste microregion presented the smallest one, with a value equivalent to 0.

Regarding Inapt class, the largest area extension is represented by the Rio Doce micro-region with 363,942.60 ha and the smallest one by the Litoral Sul micro-region, with 129,552.42 ha. Regarding Inappropriate class, the Nordeste (9,8263.6 ha) and Caparaó (94,543.83 ha) micro-regions presented the largest areas. The smallest area was represented by the Central Serrana micro-region (9,479.35 ha).

DISCUSSION

Isolated variables

From the results presented in Table 1, it is possible to affirm that micro-regions with larger proportions of areas suitable for Eucalyptus genus are: Nordeste (ND) and Noroeste (NR). These two regions have, respectively, 702,123.45 ha and 601,817.39 ha of favorable edaphoclimatic aptitude ranges. These results demonstrate the enormous productive potential of the Espírito Santo state for the studied species, in this case, ~~of~~ planted forests. This potentiality is proven by the fact that ES has managed to secure, in recent years, the 6th national place in the production of eucalyptus wood despite being on the 23rd position on territorial extension ranking among Brazilian states (IBÁ, 2017).

It is important to highlight that the Rio Doce (RD) and Sudoeste Serrana (SS) micro-regions, which presented the highest rates of ineptitude for eucalyptus plantations, have their source of income mainly from agronomic crops. These include coffee growing, fruit growing (papaya, sugar cane and coconut) and corn cultivation in Rio Doce, and bean, potato, banana, tomato and coffee in Sudoeste Serrana (IJSN, 2014).

According to Table 2, the Nordeste and Rio Doce micro-regions presented larger proportions of areas suitable for machine implementation regarding slope, being represented by 800,045.71 ha and 648,738.57 ha, respectively. These are the micro-regions with the largest coastal perimeter of the state, showing that they tend to have flatter relief than the others.

About 5.20% of the state area represents the limited fitness class, with slope between 27.1 - 35º. Regions with the most areas within this fitness class were: Caparaó (40,096.72 ha) and Sudoeste Serrana (38,683.60). These micro-regions are located in southern state regions, far from the coast, where undulating to very undulating reliefs predominate, resulting in greater difficulties for forest machine use.

Although aptitude class with 0 - 27º slope is present in all microregions, 1.96% of the state area does not allow mechanization in the harvesting process, since these regions have slopes greater than 35º. In this sense, the Noroeste (17,401.64 ha) and Central South (16,386.60 ha) regions stand out for being located farther from the coast and further south of the state, presenting the highest rates of disability regarding this variable (> 35º).

Regarding land use and occupation, from Table 3, it can be seen that the Nordeste (477,784.01 ha) and Noroeste (419,735.24 ha) micro-regions have the largest extensions of land with suitable class coverage for implementation and mechanization of forest activities. Pasture, macega and areas with planted forests are among the main influencing classes in these regions. This can be explained because together, the aforementioned micro-regions correspond to about 38% of the pasture in the whole state, although 39% of the areas are destined for planted forests, 30% are of exposed soil and 24% of macega. These classes are defined as suitable for mechanization as well forest implantation in the present study.

The Nordeste and Rio Doce micro-regions presented the largest area extensions classified as type II limited (71,070.67 ha and 19,980.59 ha, respectively). This fact can be corroborated by (IBGE, 2020) data that highlights the importance of annual agriculture (corn, sugar cane, tomato, which, although perennial, is cultivated as annual) for these micro-regions.

Class fit with limitation type III, represents 133,550.08 ha of the state, being present in all microregions, especially in Nordeste and Rio Doce. In this case, the limiting factor to mechanization is land use and occupation, which made it impossible to determine developed activities in those locations. Therefore, to implement forest activities in regions with type III limitation, it is necessary to verify their use in the field.

Combined variables

By combining soil and climate zoning with slope, land use and improper areas, and then applying the minimum area limitation, results slightly differed from the individual variable evaluation. Based on Table 4, Espírito Santo has 39.45% suitable areas to implement Eucalyptus and mechanized wood harvesting, without the need of auxiliary traction winches, as these regions have climate, vegetation, soil and slopes inferior to 27º, as well as land use and occupation that allows for forest cultivation and their related activities. On the other hand, 47.91% of Espírito Santo lands are unsuitable to mechanized harvesting, since they are areas with slopes greater than 35º and/or do not favor Eucalyptus introduction, due to edaphoclimatic characteristics.

In general, edaphoclimatic zoning directly reflected harvesting mechanization aptitude in the evaluated area. This is why the Noroeste region, which, by its slope, stood out among regions with the greatest disability. When confronted with land use and occupation data and zoning itself, it became the second most prone state micro-region. The Nordeste region, in contrast, stood out in all variables, thus justifying its sovereignty vis-à-vis the other microregions regarding the proportion of suitable areas. Together, these micro-regions total more than 770 thousand hectares of areas suitable for harvesting mechanization, which corresponds to about 17% of the entire territorial extension of the Espírito Santo State.

These micro-regions are located near large pulp and paper industries present in the cities of Aracruz-ES and Mucuri, far south of Bahia. In addition, some cities in these regions, such as Conceição da Barra and São Mateus, are among the 20 largest cities to produce wood for pulp and paper. High forest species productivity, along with suitable area availability and declivity below 27º, allows for a higher level of mechanization in Nordeste and Noroeste micro-regions. Moreover, their edaphoclimatic characteristics favor Eucalyptus cultivation while geographical location favors flatter reliefs.

Rio Doce and Centro Oeste micro-regions, on the other hand, do not present favorable edaphoclimatic or topographic characteristics to forest activities involving studied species under mechanized systems. This is because their territory adds an area of 646 thousand hectares unfit for this type of production system. This value corresponds to 29% of the total unfitted areas of this study and 14% of the entire state area.

The main influencing variables, in this case, were zoning, where Rio Doce corresponded to 200 thousand hectares of disability, and land use and occupation, which together with Centro Oeste, accounted for 580 thousand unfit hectares. The Metropolitana and Rio Doce micro-regions had the largest extensions of land requiring ATW's. These two microregions together make up 3,582.91 hectares, which corresponds to less than 1% of Espírito Santo State.

ATW use will allow mechanization on sloping terrain, replacing manual and semi-mechanized systems. By adopting a mechanized system, production costs and the number of accidents during operation reduces, making it highly attractive (COSTA *et al.*, 2017; LEITE *et al.*, 2012; SOUZA; PIRES, 2009). Although its use has the potential to redistribute power between wheelsets, which increases traction capacity, it is always important to remember that wood harvesting will have a productivity deficit due to coupling and disengagement ATW at anchor points (Lopes *et al.*, 2016).

According to Holzfeind *et al.* (2018), during extraction operations, ATW use is very important in steeply sloping regions. However, in their experiment, ATW, when coupled with Forwarders, added about 16% of final harvest costs. Visser *et al.* (2014) have been able to develop a work that clearly demonstrates ATW's importance in step cutting. In their study, authors showed that a 37-ton Harvester with a 40% traction coefficient begins to slide when the slope reaches 22 degrees, but with an auxiliary traction winch, tractive force is increased by 10 tons of force, making it able to operate on slopes up to 37º, close to the considered range in the present study.

With map algebra and limitations, the Nordeste region remained with the largest territorial extension of areas larger than 10 linear hectares of annual cycle crops. In addition, the Litoral Sul region, which previously represented the third position regarding this variable, moved to the second, showing that the fragmentation of productive sites is smaller than Rio Doce, which assumed the former Litoral Sul position.

Sugarcane cultivation in the Espirito Santo state occupies approximately 60 thousand hectares, being the most produced short-cycle species (GALEANO *et al.*, 2018). Cities in Nordeste and Litoral Sul are highlights in this type of agricultural product, such as: Conceição da Barra; Pedro Canário; Pinheiros; Itapemirim; and Montanha (GALEANO *et al.*, 2017). These micro-regions include cities with the highest sugarcane productivity, and together have 67,000 hectares of area suitable for mechanization, however, with land use and occupation intended to short-cycle agriculture.

In addition to sugar-cane, corn stands out with 40 thousand hectares spread throughout the state (SILVA; SILVA, 2017). Thus, corn cultivation may be a limiting factor to forest production, since it occupies suitable regions regarding slope. Pineapple production in the state can also be highlighted, and in recent years Litoral Sul had 21.76% of GDP in 2014 (IJSN, 2014). These crops' development impedes the growth of forest enterprises, although declivity allows for introduction of planted forests using mechanized harvesting systems.

Conservation Units' presence shows that a large area of Espírito Santo must be preserved and that activities around it, within its buffer zones, must follow specific rules, requiring prior evaluations and authorizations for planted forest cultivation. Improper areas were responsible for a suitability decrease of 10.5% of the total state area (48561.4 ha), highlighting Nordeste and Caparaó micro-regions. Caparaó National Park, located between Minas Gerais and Espirito Santo States, Córrego Grande Biological Reserve, Rio Preto National Forest, Córrego do Veado Biological Reserve and their respective buffer zones, presented in both micro-regions, included 4.18% of the entire state.

CONCLUSIONS

The analysis carried out allow us to conclude that:

- The Espírito Santo state has 39.45% of its territory able to implement *Eucalyptus* as well as mechanized wood harvesting, while 47.91% of its extension is considered unfitted for these purposes.
- The Nordeste micro-region stood out as the largest proportion of areas suitable for harvest mechanization, which corresponds to approximately 17% of the entire territorial extension of Espírito Santo. Rio Doce and Centro Oeste micro-regions do not present favorable soil and climatic characteristics to forest activities involving studied species under mechanized systems.
- Results regarding slope, land use and occupation, as well as *Eucalyptus* edaphoclimatic zoning, are fundamental for planning and decision-making to increase production, reduce costs and optimize the available resources.
- This methodology has potential and can be adapted to other areas of study around the world.

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