Article

revista
GeoUSP
espaço e tempo
Volume 27 • n° 2 (2023)

ISSN 2179-0892

Permanent Preservation Areas (PPA) on hilltops in two crystalline massifs of Florianópolis, Santa Catarina: application to different relief models according to the delimitation criteria of the repealed Brazilian Forest Code and the new law for the protection of native vegetation

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e-193254

How to cite this article:

BERNARDES, M. P.; LUIZ, E. L. Permanent Preservation Areas (PPA) on hilltops in two crystalline massifs of Florianópolis, Santa Catarina: application to different relief models according to the delimitation criteria of the repealed Brazilian Forest Code and the new law for the protection of native vegetation. **Geousp**, v. 27, n. 2, e-193254, may/aug. 2023. ISSN 2179-0892. Available at: https://www.revistas.usp.br/geousp/article/view/193254. doi: https://doi.org/10.11606/issn.2179-0892.geousp.2023.193254.en.

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Permanent Preservation Areas (PPA) on hilltops in two crystalline massifs of Florianópolis, Santa Catarina: application to different relief models according to the delimitation criteria of the repealed Brazilian Forest Code and the new law for the protection of native vegetation

Abstract

Permanent Preservation Areas (PPA) on hilltops have undergone changes in their application criteria under the new Native Vegetation Protection Law (LPVN, in Portuguese), particularly regarding the recommendations outlined in Conama Resolution 303/2002. Also, LPVN disregards the fact that the hills in Brazil have different relief models, which are determined by their geological structure and active geomorphological processes. The objectives of this article are to analyze the application of this typology of PPAs in two crystalline massifs with a dissection model in Florianópolis, Santa Catarina, and to verify possible changes in the degree of protection in relation to the criteria of the aforementioned regulations. The results revealed that in an area with relatively homogeneous geology, the relief aspects vary and influence the delineation of the PPAs. It was also observed that the LPVN criteria resulted in a 100% reduction in hilltop PPAs compared to those of the previous Forest Code and Conama Resolution 303/2002.

Keywords: Permanent Preservation Area (PPA); hilltops; crystalline massifs; environmental legislation.

Áreas de Preservação Permanente (APP) em topos de morro em dois maciços cristalinos de Florianópolis/SC: aplicação para diferentes modelados de relevo segundo critérios de delimitação do Código Florestal Revogado e da nova Lei de Proteção da Vegetação Nativa

Resumo

As Áreas de Preservação Permanente (APP) em topos de morros sofreram alterações nos seus critérios de aplicação segundo a nova Lei de Proteção da Vegetação Nativa

(LPVN), especialmente em relação ao que é preconizado na Resolução Conama 303/2002. Também, a LPVN desconsidera que as elevações brasileiras possuam diferentes modelados de relevo, de acordo com sua estrutura geológica e processos geomorfológicos atuantes. Os objetivos deste artigo são analisar a aplicação desta tipologia de APPs em dois maciços cristalinos com modelado de dissecação em Florianópolis/SC e verificar possíveis mudanças no grau de proteção em relação aos critérios das normativas citadas. Os resultados revelaram que em uma área de geologia relativamente homogênea, os aspectos de relevo são diferentes e condicionam a delimitação das APPs. Também foi observado que com os critérios da LPVN houve redução de 100% das APPs em topo de morro em relação àqueles do Antigo Código e Resolução Conama 303/2002.

Palavras-chave: Área de Preservação Permanente (APP); topos de morros; maciços cristalinos; legislação ambiental.

Áreas de Preservación Permanente (APP) en las cimas de elevaciones para dos macizos cristalinos en Florianópolis / SC: aplicación a diferentes modelos de relieve y según criterios de delimitación del derogado Código Forestal y la nueva Ley de Protección de la Vegetación Nativa

Resumen

Los criterios de aplicación para Las Áreas de Preservación Permanente (APP) en las cimas de elevaciones sufrieron cambios en el marco de la nueva Ley de Protección de la Vegetación Nativa (LPVN), especialmente con relación a lo recomendado en la Resolución Conama 303/2002. Además, la LPVN no considera que las elevaciones brasileñas tengan diferentes modelos de relieve, de acuerdo con su estructura geológica y procesos geomorfológicos. Los objetivos de este trabajo son analizar la aplicación de esta tipología de APPs en dos macizos cristalinos con modelo de disección en Florianópolis/SC y verificar posibles cambios en el grado de protección con relación a las normativas mencionadas. Los resultados revelaron que, en un área de geología relativamente homogénea, los aspectos del relieve son diferentes y afectan la delimitación de las APP. También, de acuerdo con los criterios de la LPVN, hubo una reducción del 100% de estas APPs con relación a los del derogado Código y la Resolución Conama 303/2002.

Palabras clave: Área de Preservación Permanente (APP); las cimas de elevaciones; macizos cristalinos; legislación medioambiental.

Introduction

The institution of the Native Vegetation Protection Law (Law no. 12.651/2012), also known as the New Forest Code, caused many changes in Brazilian environmental legislation. In relation to the typologies considered as Permanent Preservation Areas (PPAs), little has changed from what was already recommended in the repealed Forest Code Law (Law No. 4,771/1965); the protection of mangroves in the new law became clearer, for example. All categories of existing PPAs remained, but there were changes in the criteria for their identification. This was the case for PPAs on hilltops. The criteria for delimiting this typology of PPAs underwent changes, which included the removal of ridge line protection (as stated in Conama Resolution No. 303/2002).

In addition, Brazilian environmental legislation establishes unique criteria for the delimitation of hilltop PPAs that do not consider the variations in hilltops and different types of hills found in some areas controlled by different lithologies and geological structures (structural reliefs). For example, there are reliefs characteristic of structures with horizontal and sub-horizontal layers (sedimentary rocks and/or lava spills), volcanic activity, failed and folded areas, and crystalline intrusions (PENTEADO, 1983; PISÓN; TELLO, 1986; PENHA, 1994; CASSETI, 2005). Penha (1994) also highlights the foliation of metamorphic rocks as a characteristic that interferes with relief modeling, and several authors (PENTEADO, 1983; PISÓN; TELLO 1986; CASSETI, 2005; GOUDIE; VILES, 2010) draw attention to rocks with a carbonate composition that develop unique relief features.

According to Penteado (1983) and Casseti (2005), reliefs are differentiated by their climatic-structural relationships and can be divided into tabuliform, cuestiform, *hog-back*, and dome-shape reliefs, carved in folds (such as Jurassic and Appalachian), elaborated in a failed, crystalline structure, or on carbonate rocks (karstic relief). The hills in each of these types of relief have different shapes, which vary according to the geological structure and the dissection pattern of the local climate. In tabuliform reliefs, for example, the tops of the hills may be flat if a resistant layer is at the top, or a crest-shaped top hill may occur in reliefs that follow an old fault line. Continuous hills with extensive ridges can be observed in Appalachian-type reliefs when a resistant layer of rock, such as quartzite, is exposed.

Another issue to be raised is that in Geomorphology, it is not relevant where the top of the hills begins. This is not the object of geomorphological studies. Guerra (2008) defines the top or summit of a hill as its highest part. That is, it is a term used only in a descriptive, not delimitative, way. That is, the term is used solely in a descriptive manner, rather than a delimitative one. Therefore, it is important to conduct studies in Geomorphology that focus on delineating hilltop PPAs, considering the various structural reliefs and rock characteristics. This could contribute to a more effective implementation of the legislation or to its revision.

Several studies focus on hilltop PPAs in Brazilian locations, but they do not utilize geomorphological knowledge or provide a detailed analysis of the relief being studied. Some of these studies were concerned, still within the criteria established by the repealed Forest Code and Conama Resolution n. 303/2002, with the development of automated methodologies in the Geographic Information Systems (GIS) environment for the determination of PPAs in hilltops. Examples of such studies include Peluzio, Santos, and Fiedler (2010), Oliveira (2002), and Hott, Guimarães, and Miranda (2005), among others. Peluzio, Santos, and Fiedler (2010) found 3.886km ² of a permanent protected area on hilltops and ridge lines in the Alegre River basin, ES. Oliveira (2002) discussed the automated application of criteria for defining a hilltop PPA in the Paraíso stream basin in Viçosa/MG. Hott, Guimarães, and Miranda (2005) utilized an automated methodology in a Geographic Information System (GIS) environment to map the typology of this PPA for the entire state of São Paulo. They identified a total of 19,236 km² of protected areas. In relation to these studies, there is a diversity in the size of the analyzed areas and, consequently, in the spatial scales used.

The accuracy and spatial resolution of the planialtimetric product used to delimit the PPAs on hilltops interfere with the obtained results. The works of Victoria (2010), Oliveira (2015), Almeida and Berger (2017), and Oliveira, Cessa, and Oliveira (2020) address this issue. Victoria (2010) utilized various methods to calculate PPAs for hilltops within the same spatial area in Campinas/SP. The results showed that the extent of protected areas, as determined by the DTM (Digital Terrain Model) from the *SRTM (Shuttle Radar Topography Mission*) with a spatial resolution of 90 m, was smaller than the areas obtained from a topographic survey at a scale of 1:50,000 (25 km² and 213.1 km² respectively). Therefore, the higher the spatial resolution of the product used to identify the PPAs on hilltops, the larger the protected area.

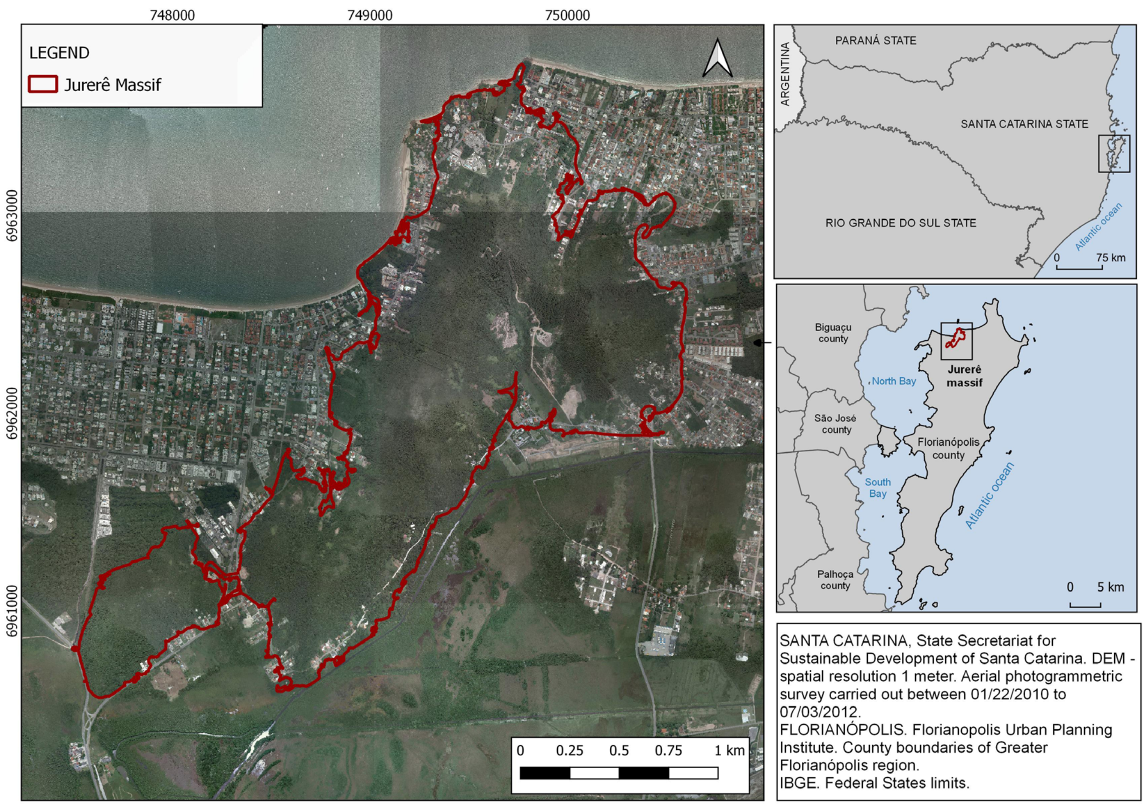
Research on protected areas as hilltops increased after Law No. 12,651/2012 introduced changes in the criteria for identifying these PPAs. Examples of such studies include Gasparini *et al*. (2013) and Luppi *et al*. (2015). Some studies compare the level of protection provided by the criteria outlined in the Repealed Code and the New Code, as demonstrated in the works of Francelino and Silva (2014) and Guimarães and Moreira (2018).

Considering that the current Law for the Protection of Native Vegetation restricts hilltop PPAs to unique criteria, without considering that there are different reliefs in the Brazilian territory, this article discusses the delimitation of PPAs on hilltops for two crystalline massifs with dissection in the form of hills and mountains located in Florianópolis county, state of Santa Catarina, whose geology is not very complex, consisting mostly of granitic intrusive rocks. The results of applying the various criteria of the Repealed Forest Code and Conama Resolution No. 303 of 2002 are also compared to those outlined in the Native Vegetation Protection Law for the two massifs under study. This is done to determine any potential changes in the protection of areas designated as hilltop PPAs.

Area of study

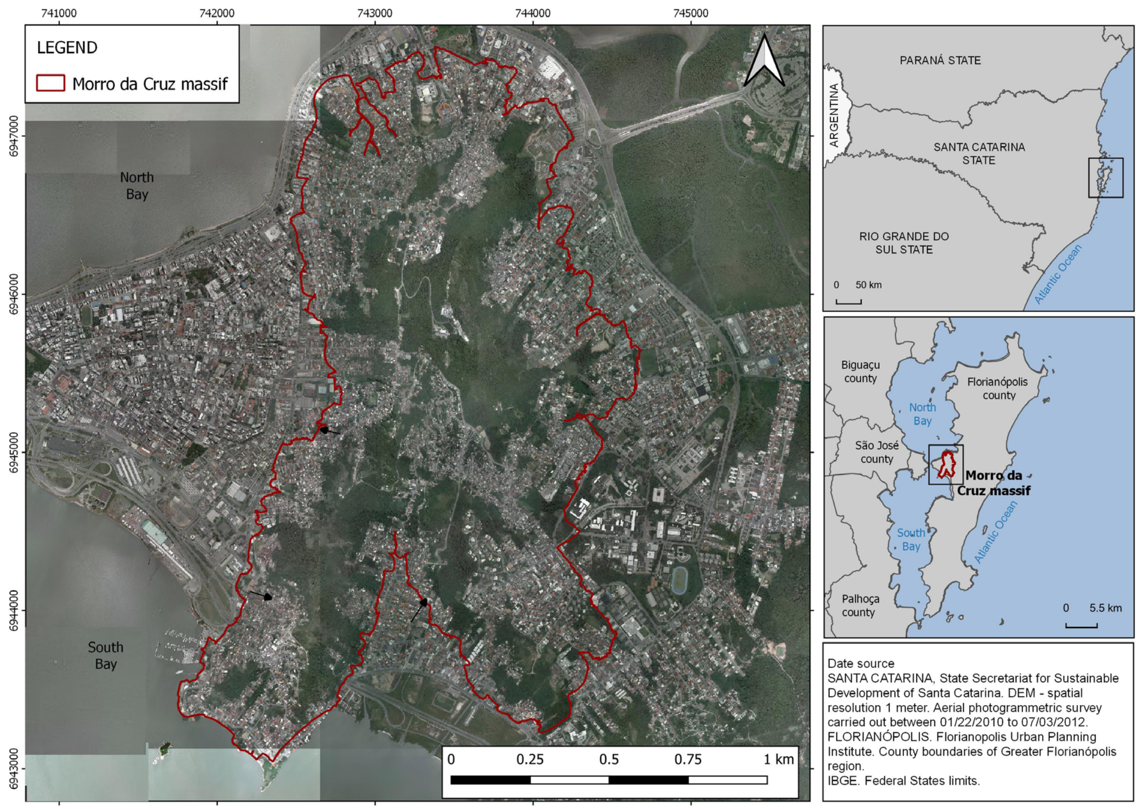
The study area comprises two massifs located in Santa Catarina island (Florianópolis county): the Jurerê massif in the northwest of the island, and the Morro da Cruz massif in the central part (Figures 1 and 2). According to Herrmann and Rosa (1991), the topography of the Santa Catarina island exhibits dissection pattern in massifs with hills and mountains, formed by Precambrian granitic rocks (CARUSO JÚNIOR, 1993).

Figure 1 – Location of the Jurerê Massif.



Source: prepared by the authors (2023).

Figure 2 – Location of the Morro da Cruz Massif.



Source: prepared by the authors (2023).

The seemingly straightforward geological structure of crystalline intrusions, consisting of various types of granites, is altered by the presence of multiple structural lineaments that primarily run in a northeast-southwest direction. These lineaments give rise to watersheds and river valleys. Some of these lineaments are filled with basic dikes (diabase) and, to a lesser extent, acidic and intermediate rocks (rhyolites, dacites, and andesites) (TOMAZOLLI; PELLERIN, 2014). It should be noted that the presence of dikes can cause contact metamorphism in the surrounding rocks, altering their resistance to weathering.

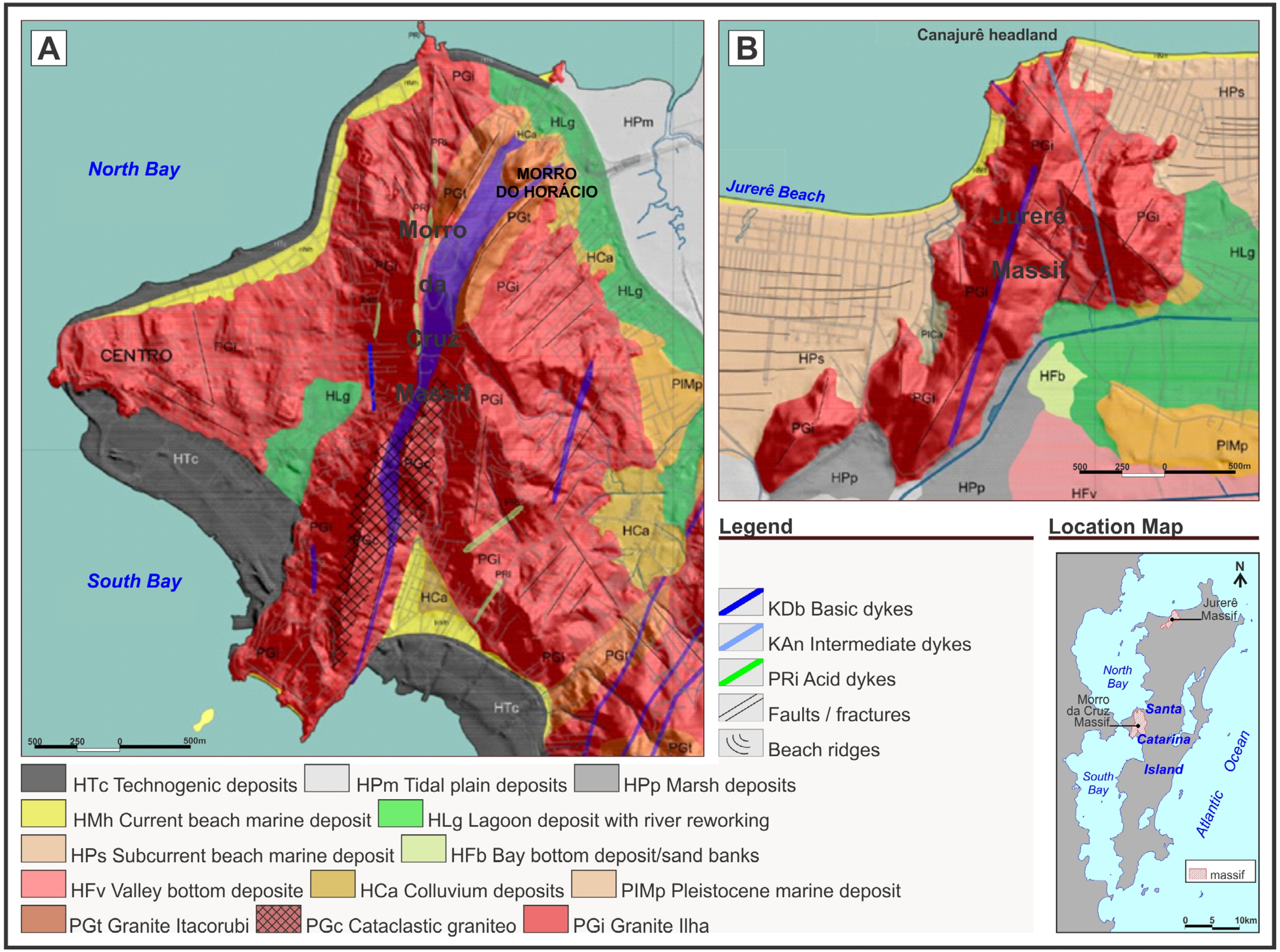
According to the mapping conducted by Tomazolli and Pellerin (2014), the Jurerê massif is composed of the Granite Ilha and exhibits numerous structural lineaments from various directions. One of these features is located in its main divide and follows a northeast-southwest direction, forming a dike of basic rocks (Figure 3). Another feature exhibits a northwest-southeast orientation and is composed of acidic rocks, situated within a secondary boundary. This massif has a maximum altitude of 148.50 m and is modeled for dissection in hills. It is surrounded by terrains of marine and lake plains, as described by Herrmann and Rosa (1991).

The Morro da Cruz massif has a more complex geology, despite being composed of the granite Ilha and granite Itacorubi. These granites have suffered significant modification due to deformation events such as shear zones and faults. Additionally, there have been late intrusions of acidic and basic rocks (TOMAZOLLI; PELLERIN, 2014). In one part of the massif, the granite Ilha was transformed into Cataclastic Granite, which has a dark hue due to higher concentrations of iron (TOMAZOLLI; PELLERIN, 2014).

The Cataclasite Granite is northeast-southwest oriented and it forms lengthy ridges in the southern part of the massif. Following the alignment of the Cataclasite Granite towards the north, there is a diabase dike. This dike becomes thicker towards the north, and above it, a valley was formed in the locality of Morro do Horácio. Rhyolite dikes are also found in this massif, approximately running in a north-south direction. One of these dikes forms another crest segment in the massif's northern part, at a slight angle to the diabase dike where the valley developed. In addition, these rocks are cut by aplite veins of varying thicknesses and directions (TOMAZOLLI; PELLERIN; ESTEVES, 2003).

The altitudes in the Morro da Cruz massif reach 286 m, and this value also represents the highest range of elevation on its slopes, as its base is located at altitudes close to sea level. Herrmann and Rosa (1991) attribute to this massif a patten of dissection in mountains, with the presence of angular interfluves. It is bounded on the west by a pattern of dissection in hills, by the waters of the bays (North and South), and by the Itacorubi mangrove swamp to the east. To the south, the Morro da Cruz massif is connected to the Costeira massif.

Figure 3 – Geological aspects of the Morro da Cruz (A) and Jurerê (B) massifs.



Source: Extracted from Tomazolli and Pellerin (2014), original scale 1:50,000. Created by the authors.

Methodological procedures

For the mapping of PPAs on hilltops, a methodology based on Souza (2021) was used, along with the free *software* QGIS *3.10*. The source of the topographic data was the digital terrain model (DTM) with an altimetric accuracy of 1 meter and a grid with a spatial resolution of 1 meter. This data was made available by the State Secretariat for Sustainable Development of Santa Catarina (SDS, in Portuguese).

Initially, the spurious depressions of the DTM were removed, using the "*Fill Sinks xxl*" tool, thus creating a hydrologically consistent model (MDTHC, in Portuguese) (SILVA *et al.*, 2016). The horizontal or base plane of the massifs studied was defined by the limit between slopes greater and less than 10% (5.71º) (SOUZA, 2021), based on the elaboration of a slope map in the tool "*Slope, aspect, curvature*".

As the hills to be mapped are in fact massifs that have several peaks (tops), it was necessary to divide these massifs into sectors in order to determine the hill associated with each peak. To identify the hills and their tops in the massif, different procedures were used: inversion of relief, generation of flow direction and delimitation of watersheds. These procedures are described in various studies, including Hott, Guimarães, and Miranda (2005), Victoria (2010), Oliveira and Fernandes Filho (2013), and Souza (2021). The inverted relief allows the peaks to be converted into depressions, and the flow direction and the division of the watersheds identify the contribution area of these inverted peaks. In this way, the contribution area will be part of the massif that represents the hill of that peak.

To create the inverted relief, the MDTHC was used, processed by the "*raster* calculator" tool from the expression "*MDTHC*(-1)*". In the inverted MDTHC, the flow direction was processed with the "*terraflow*" tool. For the generation of flow segments and the division of inverted watersheds, the "*watershed*" complement was used. Tests were conducted to determine the minimum sizes of the watershed to be used. To identify the tops, four criteria were used: 1) the intersection of the outflows determined by the inverted relief; 2) the direction of inverted flow; 3) the flow segment; and 4) the contour lines with an equidistance of 10 m that close in on themselves near the ridges. The inverted flow direction was used by Oliveira (2015), Oliveira and Fernandes Filho (2013), Peluzio, Santos, and Fiedler (2010), and Victoria (2010). Souza (2021) employed the other three criteria.

After defining the summits (peaks), the hills of which they are part in the massif are individualized. The hill, in this case, is idealized as a certain area that receives the surface runoff from the peak. The delimitation of this area is determined by the direction of flow and the boundaries of the watersheds previously developed using the inverted MDTHC method. Additionally, the "normal relief" in 3D, generated by the "*Qgis2threejs*" tool, is utilized. Based on this information, the areas belonging to each peak are manually delimited. Along the ridge line, the hills areas of each ridge line are delimited from the saddle point between them using contour lines with a one-meter equidistance. The hills along the massif are manually determined by merging the watershed that contribute to the highest point in the inverted relief using the "*merge features*" function in *QGis*, until there is a hill for each peak.

Having defined hills and their tops in each massif studied, we used the criteria established by the Repealed Forest Code (as well as Conama Resolution no. 303/2002) and the Native Vegetation Protection Law, which is currently in effect, to determine the PPA on top of a hill.

> a) Repealed Forest Code and Conama Resolution No. 303/2002: "Forests and other forms of natural vegetation located on the top of hills, mounds, and mountains are considered to be of permanent preservation, for the sole purpose of this Law" (BRAZIL. Law 4771 of 1965, Art. 2, point d).
>
> Detailing given by Conama Resolution No. 303/2002: PPAs on hilltops are identified from the upper third of the hill's elevation (with a height between 50 and 300 meters and slopes with a slope greater than 17º in the line of greatest slope) and the mountain type (with a height above 300 meters). In the event of two or more hill or mountain tops that are separated from each other by distances less than 500 meters in the ridge line, the smallest hill or mountain must be identified, and the PPA will be determined by the line of the level curve corresponding to the upper third thereof. Concerning the ridge lines, the PPA must be delimited from the level curve corresponding to two-thirds of the height, in relation to the base, of the lowest peak of the ridge, fixing the contour for each segment of the ridge line equivalent to one thousand meters (Brazil. Conama Resolution no. 303 of 2002, Art. 3, items V, VI and sole paragraph, items I, II, III and IV).

To calculate the slope and height of each hill, the "Zonal statistics" tool was used, in the same line as the work of Silva *et al*. (2016). For the hill measurements, the altitude of the surface with a slope equal to or less than 10% (17º) was taken as the base of the massifs, and the altitudes of their tops were calculated. The hills that met both criteria, which were a slope greater than 17º and a height greater than 50 meters (according to Conama Resolution n. 303/2002), were selected to determine the PPAs on hilltops.

Conama resolution no. 303/2002 draws attention to tops that are in a ridge line. These ridges are not 500 meters apart from each other. If they are further away than that, they are configured as isolated tops or new ridge lines. To know if the identified tops are part of a ridge line, the distance between them was measured with *QGis's* tool called "*lines*". As resolution determines that the lowest hill that is part of the ridge line must be identified to be the basis of the delimitation of the protected areas as a hilltop for the entire ridge line, it was identified by its height. After identifying the hill with the lowest height, its upper third was determined in the "*field calculator*" by the expression: "'*height_max*' - ('*amplitude_height*' /3)" of the QGis. This upper third was then expanded to the entire ridge line, since it did not exceed 1,000 meters in length of the ridge line (BRAZIL, CONAMA Resolution No. 303/2002, Art. 3, item VI). Branches of ridges lines in the studied massifs were observed when the hills were identified and delineated.

Since it was working with a DTM with good spatial resolution, the level curves with an equidistance of one meter were used to delimit the PPA by the value of one-third of its hill, respecting the limit of each hill, and later the PPA areas were acquired by the *"lines for polygons"* tool of the *QGis*.

To define the PPAs on hilltops of isolated hills or ridge line segments with peaks more than 500 meters apart, the process was carried out in the same manner. With the height and slope calculated, it was only a matter of calculating the third of the height with the *"field calculator"* in accordance with the expression used previously. To delimit the polygons of PPAs, level curves with an equidistance of 1 m were also used in the *"lines for polygons"* tool.

> b) Native Vegetation Protection Law: PPAs are defined as the highest points of hills, mounds, and mountains, with a minimum height of 100 meters and an average slope greater than 25º. These areas are delimited by the level curve corresponding to 2/3 of the minimum height of the hill, always in relation to the base. The base is determined by the horizontal plane defined by an adjacent plain or water body, or, in undulating reliefs, by the value of the closest saddle point to the hill (BRAZIL, Law No. 12.651/2012, Art. 4, item IX).

For the mapping of hilltop PPAs following these criteria, hills that had a minimum height of 100 meters and an average slope greater than 25 degrees were identified. These procedures were applied to the previously segmented hills in each massif studied. When the hills met these requirements, they were considered suitable for delineating the PPAs. Then, the PPA definition criteria would be applied on hilltops for undulating reliefs and isolated hills.

Results and Discussions

In this segment, the importance of defining the minimum size of watersheds in inverted relief for the process of defining Protected Areas (PPAs) on hilltops is presented and discussed. Also, the aspects of the relief influencing the application of delimitation parameters for these PPAs, as well as the differences in the quantity and size of areas considered as PPAs according to the criteria established in the Repealed Forest Code (and Conama Resolution 303/2002) and the Native Vegetation Protection Law are examined. The first two items of the results are crucial for applying the criteria outlined in both the Native Vegetation Protection Law and the repealed Forest Code.

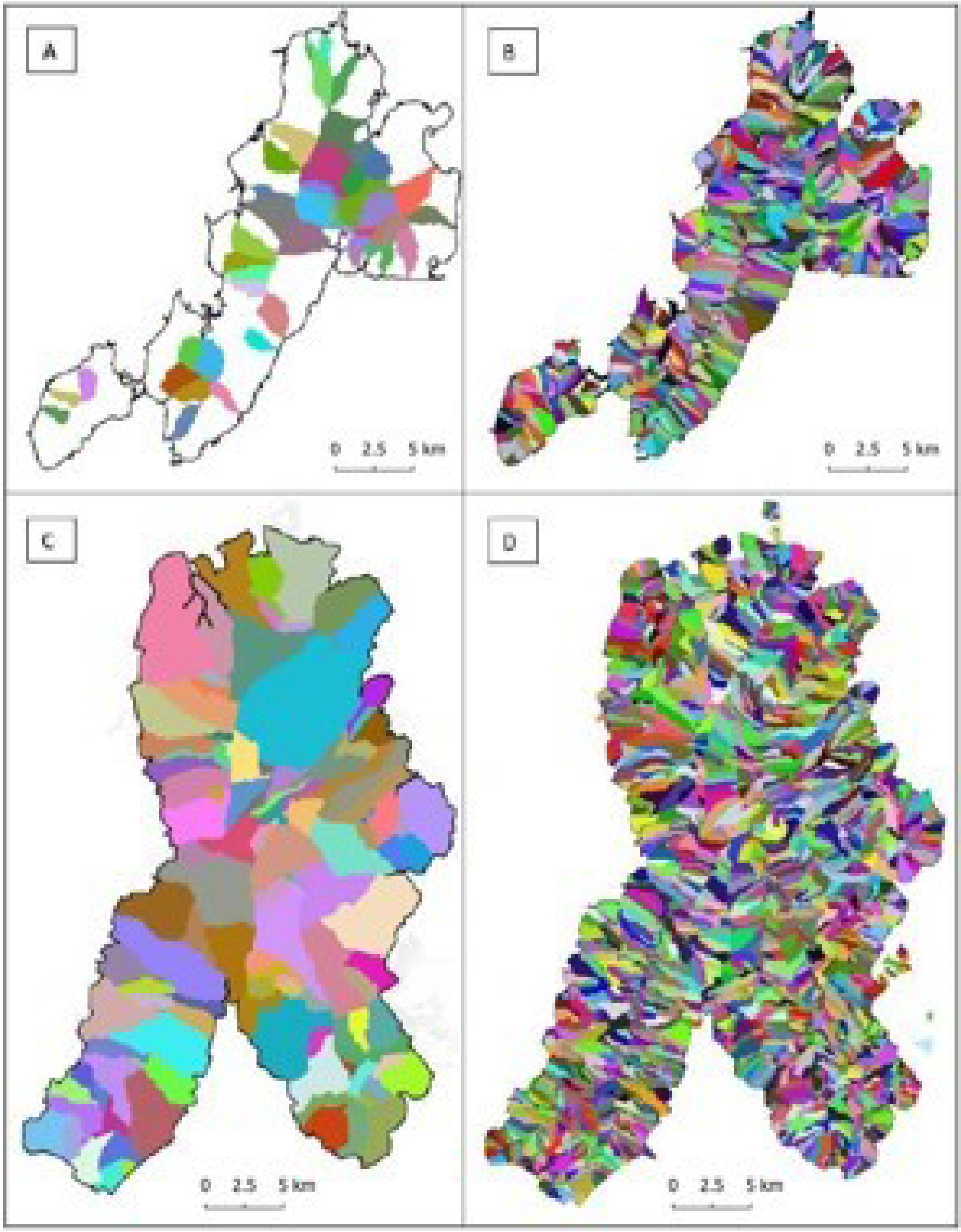
1. Definition of the minimum size of watersheds

As described in the methodological procedures, when working with massifs relief (undulating relief), it is necessary to identify and differentiate the peaks on the ridge lines and the areas of these massifs that contribute to the hills associated with each of these peaks. To achieve this, it is necessary to divide the contribution areas (watershed) in the inverted relief.

Thus, the minimum size of the watersheds to be processed must be defined; that is, the minimum number of pixels of the DTM that should be considered. For this study, the initial criterion was to use a minimum size of 0.1% of the total number of pixels that comprise each massif area.

As stated by Souza (2021), this method is highly sensitive to the minimum size assigned to the watershed and the resolution of the DTM. In the Jurerê massif, a minimum size of 10,000 pixels was used, which represents 0.1% of the total number of pixels. However, the generated watershed did not completely fill the massif, as shown in Figure 4. Through testing, the number was reduced to ensure coverage of the entire length of the massif, resulting in watershed with a minimum size of 500 pixels.

Figure 4 – Minimum watershed size for the Morro da Cruz and Jurerê massifs. Jurerê Massif: 10,000 pixels (A) and 500 pixels (B); Morro da Cruz Massif: 15,000 pixels (C) and 500 pixels (D).



Source: prepared by the authors (2023).

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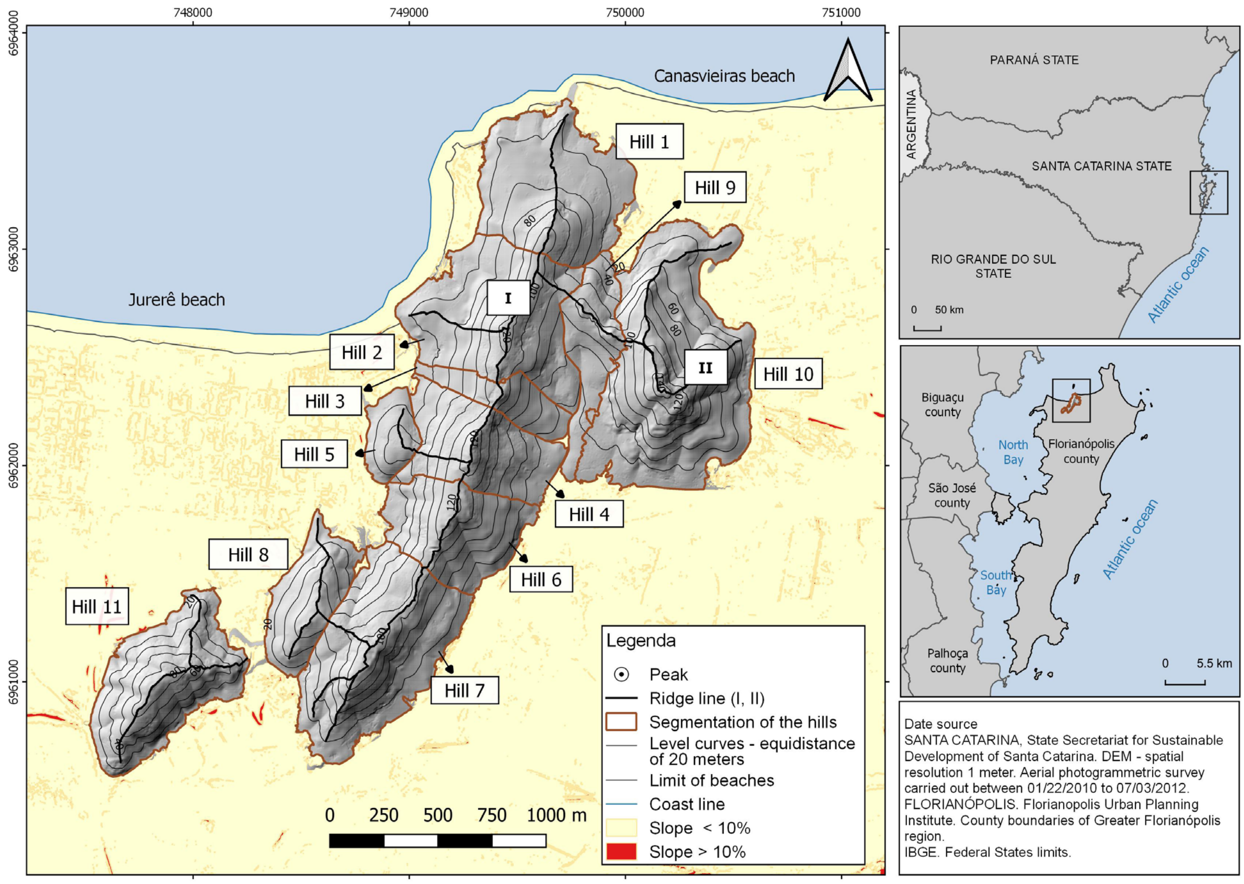
For the Morro da Cruz Massif, the utilization of a minimum size of 0.1% of the total pixel count (equivalent to 15,000 pixels in this instance) enabled the complete coverage of its entire length with watershed. This facilitated the mapping of hilltop PPAs. However, it was observed that not all possible ridges lines present there were delimited by this minimum watershed size. And a new generation of watersheds with a minimum size of 500 pixels was conducted, which is the same size used in the Jurerê massif. This minimum watershed size revealed a greater number of ridges lines (along with the corresponding hills) in the Morro da Cruz massif.

2. Relief features of the Jurerê and Morro da Cruz massifs are involved in the delimitation of Protected Areas (PPAs) on hilltops.

In the Jurerê Massif, using a minimum watershed size of 500 pixels, we found 11 peaks. Six of these peaks run along a main ridge line in a northeast-southwest direction (ridge line I). Two peaks are located at lower hills, parallel to the main ridge line. Two peaks were also identified in a secondary ridge line with northwest-southeast direction (Cumeada II). Lastly, there is a peak on a hill that has become almost isolated from the massif due to erosive wear over time (Figure 5).

Figure 5 – Relief features in the Jurerê Massif in the minimum watershed size of 500 pixels.



Source: prepared by the authors (2023).

The ridge lines follow the basic rock dike (ridge I) and acid rock dike (ridge II). The basic rock dikes in humid climates, like the one in the study area, tend to be more weathered and eroded, resulting in lower reliefs. However, it is possible that the intrusions created locally more resistant rocks in the current ridge line through contact metamorphism in the walls of the pre-existing granite. In the case of the acid rock dike, these rocks are naturally more resistant to weathering and erosion. The presence of numerous peaks in this massif, each separated by distinct saddle segments, indicates that the rocks responsible for the hills are durable, yet have been eroded over time.

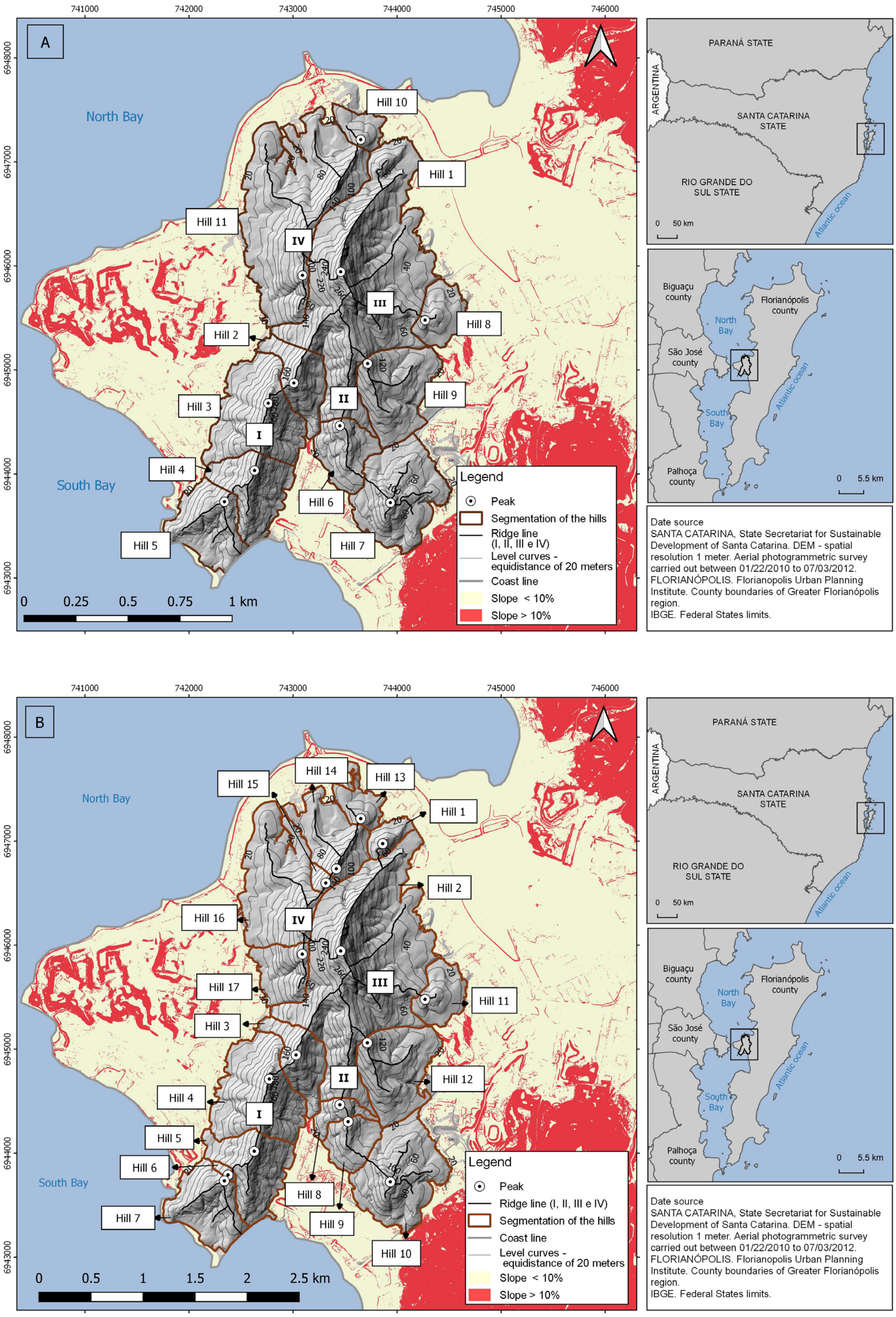
In the Morro da Cruz massif, when using a minimum watershed size of 15,000 pixels, 11 peaks were found. However, when the minimum watershed size is reduced to 500 pixels, the number of peaks increases to 17 (Figure 6).

Even though the minimum size of watershed has changed, the Morro da Cruz massif has fewer peaks compared to the Jurerê massif. This is because the area of the Morro da Cruz massif is twice as large as that of the Jurerê massif, with respective sizes of 7.64 km² and 3.38 km². This is explained by the greater resistance to weathering and erosion of the rocks in this massif. In this case, Cataclastic Granite, rocks with contact metamorphism, and acidic rocks in the form of dikes (Figure 3) exhibit this resistance. These rocks maintain continuous crest-shaped tops, and only in some places have these crests been eroded, forming saddles and peaks. This has also caused the saddle dots along these ridges to become elongated and not very deep.

The crest maintained by the Cataclastic Granite (ridge I) to the south in the Morro da Cruz Massif forms a longer ridge line. When using a minimum watershed size of 15,000 pixels, there are four peaks present. However, when the minimum watershed size is reduced to 500 pixels, there are five peaks. The northern portion of this ridge line is modeled on another material, the rocks of the Granite Itacorubi, which have undergone contact metamorphism due to the intrusion of the basic dike. It is in this section that the massif reaches its highest altitude, at 286 meters. This part of the massif forms a more continuous crest, with either one ridge when using 15,000 pixels or two ridges when using a minimum watershed size of 500 pixels. This depicts that the rocks with contact metamorphism are the strongest in the Morro da Cruz massif. The higher altitude crest can also contribute to the deformation that occurred before the formation of the Cataclastic Granite, as it is aligned with it.

It is interesting to note that there is a crest, parallel to the northern section of ridge line I, on the other side of the basic dike. This ridge line is referred to as ridge line IV. Thus, it is also modeled on rocks with contact metamorphism. In addition, this ridge line can also be influenced by a thin rhyolite dike that is aligned with it, as depicted in Figure 3. Regarding its peaks, ridge line IV was highly influenced by the minimum size of watershed used. With a watershed size of 15,000 pixels, this ridge line had two peaks, whereas with a minimum size of 500 pixels, the number of peaks increased to five. The explanation for these results is that in this section of the crest that makes up the ridge line IV, the rocks are more resistant.

Figure 6 – Relief features in the Morro da Cruz massif with minimum watersheds sizes of 15,000 pixels (A) and 500 pixels (B).



Source: prepared by the authors (2023).

Ridge line II is located in the southern part of the massif, laterally following ridge line I. It is modeled on rocks of the Granite Itacorubi and a section of it follows a structural lineament (Figure 3). Also, two rhyolite dikes cut through this ridge line. Regarding the peaks found in ridge line II, there are two of them when the minimum watershed size is set at 15,000 pixels. However, when the minimum size is reduced to 500 pixels, there are three peaks.

Ridge line III does not change its number of peaks in relation to the minimum size of the watersheds and is also modeled after rocks from the Granite Itacorubi. The part of this ridge line with higher altitudes is the one that connects with ridge line I and it follows a structural lineament (Figure 3). In one of its hills, a basic dike emerges.

A hill was considered isolated in this massif, hill 12, but it only exists when using the minimum watershed size of 500 pixels. Thus, following the peaks, 11 hill were identified in the Morro da Cruz massif for a minimum watershed size of 15,000 pixels, and 17 peaks were identified for a minimum watershed size of 500 pixels. The heights of these peaks ranged from 57m to 283m. The maximum height found for one of the hills of 283m shows that it begins near sea level, since the highest altitude of the Morro da Cruz massif is 286m. The slopes can be very steep, ranging from 41º to 66º.

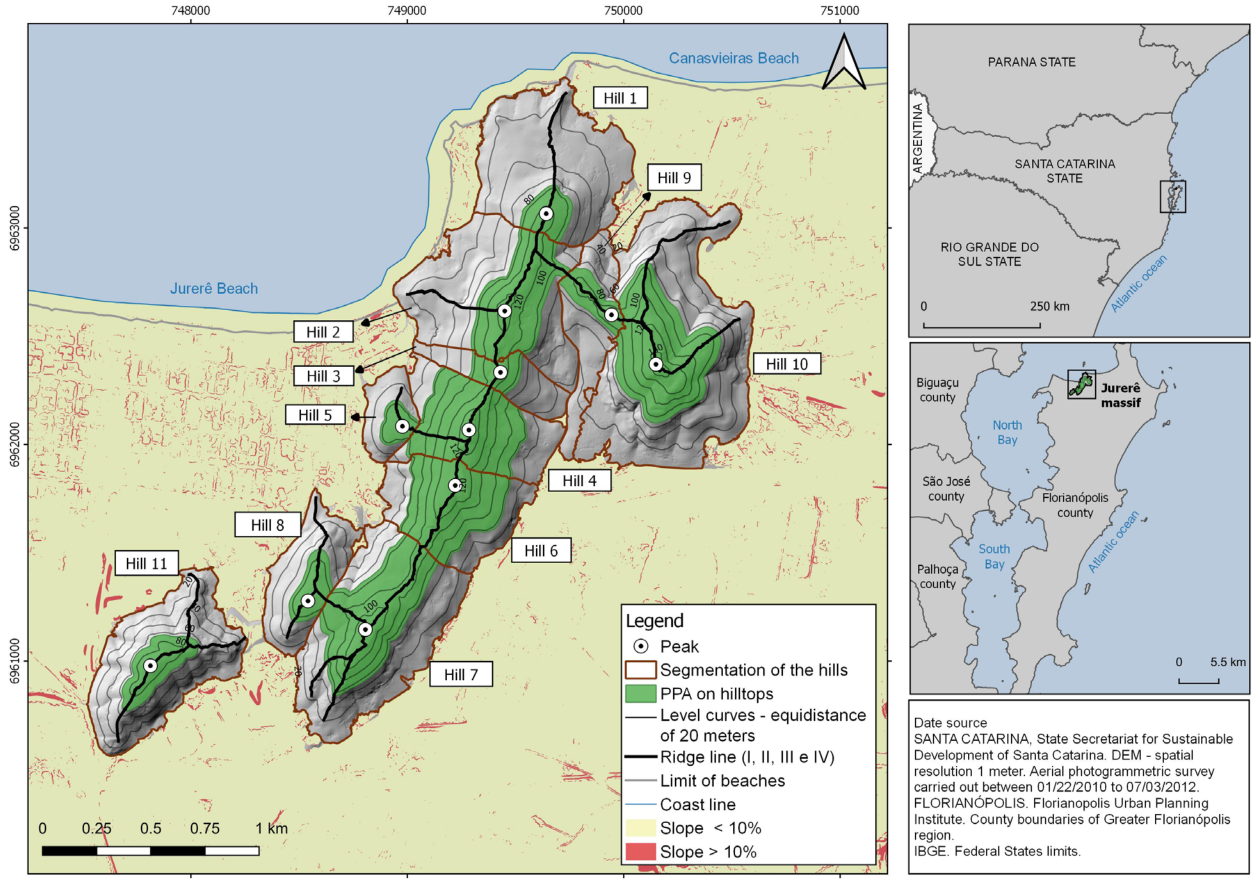
It appears from the description that the relief of the two massifs are influenced by their geological characteristics, such as lithology and structural lineaments. This is despite the presence of intrusive crystalline rocks in the regional framework, which would suggest a greater geological uniformity.

3. Delimitation of PPAs on hilltops in the Jurerê and Morro da Cruz massifs according to the criteria of the repealed Forest Code and Conama Resolution No. 303/2002

For the Jurerê massif, all 11 hills identified received protection for their upper thirds, based on the mapping of PPAs carried out according to the criteria established by the Forest Code (Revoked) and Conama Resolution No. 303/2002 (Figure 7). The ridge line criterion was used to determine the boundaries of the PPA on the hill, with the exception of the isolated hill to the southwest.

Four stretches of ridge lines in the Jurerê massif had their summits (peaks) considered PPA. The PPAs were independently mapped in each of these stretches, resulting in variations in the width of the PPA strip along the ridge lines. Three stretches followed the main ridge (ridge line I): the first stretch is formed by hills 1, 2, and 3, starting at the 74-meter level curve; hills 4, 5, and 6 form another stretch, with protection from the 37-meter line; the third stretch comprises hills 7 and 8, with the PPA defined by the 53-meter level curve. The last ridge line segment to be analyzed, is is equivalent to Ridge line II of the Jurerê massif, which runs in a northwest-southeast direction and includes hills 9 and 10. The PPA is defined by the 67-meter contour line. Hill number 11 was mapped using the methodology of isolated hills, and its PPA was defined by the 66-meter level curve.

Figure 7 – Hilltop PPAs in the Jurerê area, using a minimum watershed size of 500 pixels, in accordance with the criteria of the Revised Forest Code and Conama Resolution No. 303/2002.



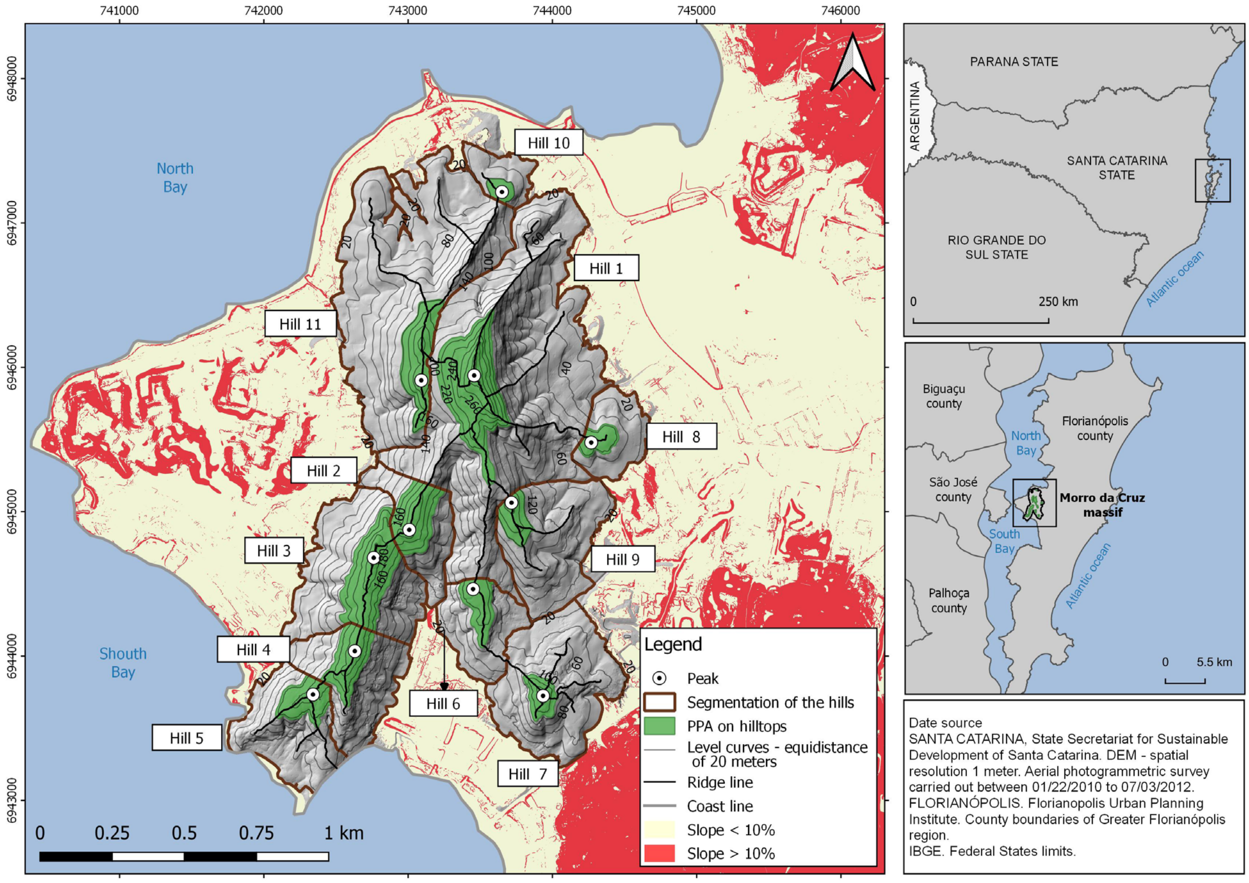
Source: prepared by the authors (2023).

The protected area on the hilltop of the Jurerê massif, as defined by the Repealed Forest Code and Conama Resolution No. 305/2002, covers 1.14 km², which is equivalent to 34.13% of the total area of the massif.

According to the provisions of the current Native Vegetation Protection Law, none of the 11 hills were identified as suitable for protecting their upper thirds. Hills 5, 8, 9, and 11 did not meet the minimum height requirement of 100 m, with heights of 51.60 m, 76.46 m, 99.33 m, and 97.74 m, respectively. And all hills found in this massif do not have an average slope greater than 25°. The highest average slopes were recorded at hill 6 (20.11°) and hill 11 (21.38°).

For the Morro da Cruz Massif, the areas protected as hilltop PPAs in all 11 hills are determined based on the criteria defined by the Revoked Forest Code and Conama Resolution n. 303/2002. These criteria require a minimum watershed size of 15,000 pixels (Figure 8).

Figure 8 – Hilltop PPAs in the Morro da Cruz Massif, using the minimum watershed size of 15,000 pixels, according to the criteria of the repealed Forest Code and Conama Resolution 03/2002.



Source: Elaborated by the authors

The ridge line methodology was only used for one section of the main ridge line (ridge I). In the remaining hills of this massif, the PPAs were calculated using the methodology of isolated hills, as these peaks are more than 500 meters apart from each other. This is a result of continuous ridges lines being supported by more resistant rocks, which is caused by contact and friction metamorphism and the presence of acid rock dikes, as mentioned before.

The section of the main ridge line (ridge line I) in which the PPA delimitation criterion by ridge line was applied included hills 2, 3 and 4. The highest point of the lowest hill in this section was used to determine the PPA, which was established based on the 74m contour line. The PPAs of the remaining hulls in ridge line I followed the criteria of isolated hills. Therefore, the PPAs of the hills considered isolated were established based on the following level curves: hill 1 (curve 192m), hill 5 (curve 74m), hill 6 (curve 70m), hill 7 (curve 87m), hill 8 (curve 56m), and hill 9 (curve 119m). In ridge line IV, hill 10 was delimited from the 41 m level curve and hill 11 had its PPA mapped by the area above the 138 m level curve.

Thus, using a minimum watershed size of 15,000 pixels, the Morro da Cruz massif has all of its hills with PPAs according to the criteria established by the repealed Forest Code and Conama Resolution No. 303/2002. The area protected as a hilltop PPA by these laws is 1.2 km², equivalent to 16.28% of the total massif.

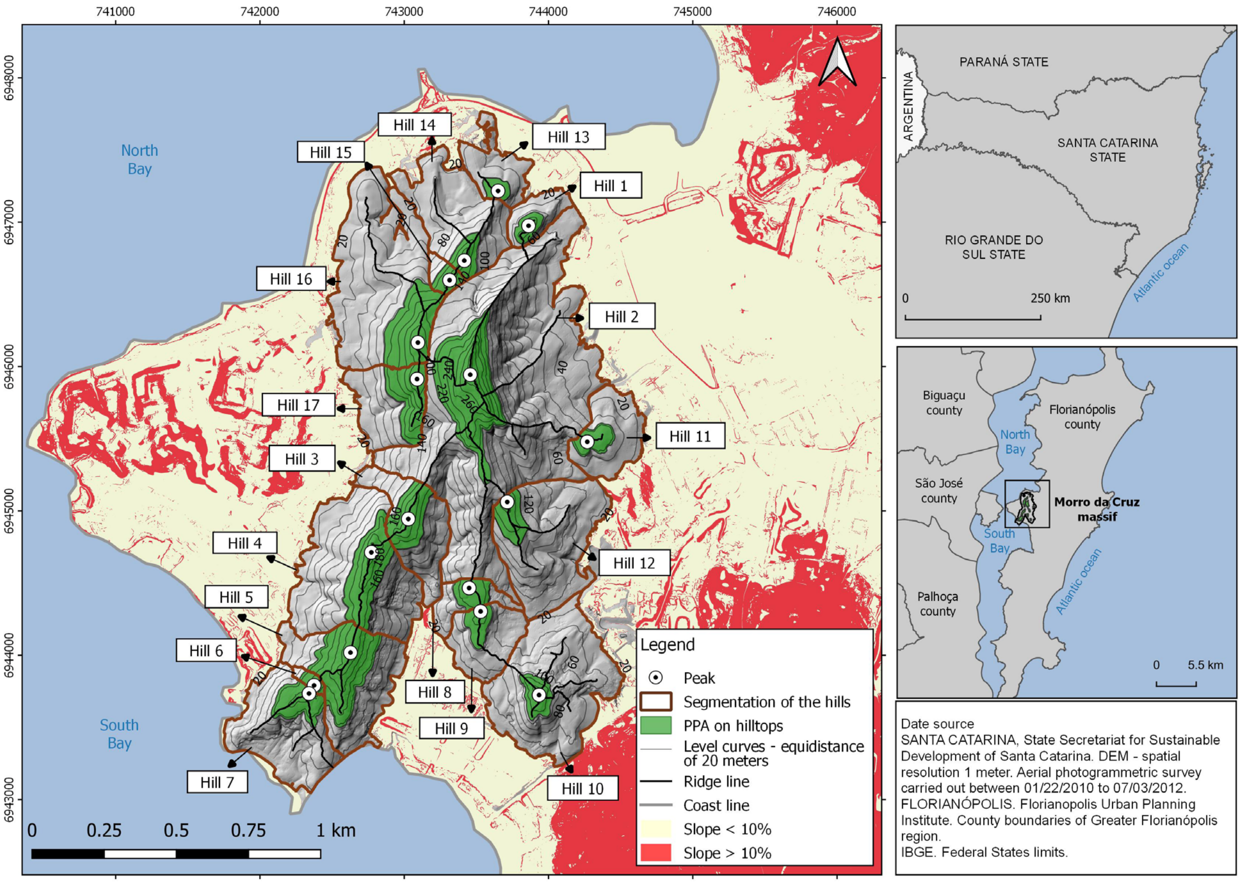
When using a minimum watershed size of 500 pixels, the Morro da Cruz massif has 17 peaks, which is six more than in the first mapping. In this way, there are more summits to be considered in terms of protection. In this minimum watershed size, two sections of the ridge line received protection, in accordance with the criteria of the repealed Forest Code and CONAMA Resolution No. 303/2002. In the section containing hills 3 and 4, the upper third that defines the PPA was delimited by the 122m level curve. In the other section, where hills 5, 6 and 7 are, the PPA was established from the 73m level curve.

The ridge line IV received more protection strip along its extension with a watershed size of 500 pixels. This ridge line has a stretch of less than 1,000 meters, where hills 14, 15, 16, and 17 are located. The summits (peaks) of these hills are less than 500 meters apart from each other. Therefore, the ridge line criterion was also used to determine the hilltop PPAs. In this case, the PPA is determined by the upper third of the lowest hill present in the ridge line. The 103m level curve is identified as the lower limit from which this PPA range begins. Also, there is another section of the ridge line containing hills 8 and 9 that received protection from the 64 m curve. The other hills of the massif were considered as isolated peaks because they are more than 500 meters apart from each other. Their upper thirds were determined by dividing the total height into three equal parts. These hills are: hill 1 (curve 46m), hill 10 (curve 87m), hill 11 (curve 56m), and hill 13 (curve 41m) (Figure 9).

Based on the use of a minimum watershed size of 15,000 pixels, the Morro da Cruz massif has a total protected area of 1.45 km², which accounts for 19.54% of its total area. It is observed that the size of the protected area is larger (19.54%) when using a more detailed minimum watershed size (500 pixels) compared to 15.70% when using a less detailed minimum watershed size (15,000 pixels). Souza (2021) discusses the situation of increasing the protected area as a hilltop PPA when lower values are used for the minimum size of watersheds in the methodological procedures.

To apply the criteria of the Native Vegetation Protection Law in the Morro da Cruz massif, the data was analyzed based on the establishment of a minimum watershed size of 15,000 pixels and 500 pixels. For the minimum watershed size data of 15,000 pixels, the criteria established by the law do not indicate a hilltop PPA in any of the 11 hills of the Morro da Cruz massif. When taking into account the criterion of a minimum height of 100 m, three hills do not complete this requirement, namely: hill 6, with a height of 76.84m; hill 8, with a height of 90.01m; and hill 10, with a height of 56.92m. Due to the average slope, none of the hills of the Morro da Cruz massif reached the necessary 25°, with the highest average slopes computed in hills 2 (21.77°), 4 (21.24°) and 5 (22.03°).

Figure 9 – Hilltop PPAs in the Morro da Cruz Massif were identified using a minimum watershed size of 500 pixels, in accordance with the criteria outlined in the repealed Forest Code and Conama Resolution 303/2002.



Source: prepared by the authors (2023).

Using the data of the minimum watershed size of 500 pixels for the delimitation of the PPAs in the Massif da Cruz, following the criteria of the current law in force, no hilltop PPAs were found. Of the 17 hills, six had heights below 100 meters: hill 1 (62.63 m), hill 6 (76.84 m), hill 8 (90.01 m), hill 9 (80.22 m), hill 11 (76.58 m), and hill 13 (57.29 m). The average slope was once again a limiting factor for hilltop PPAs. None of the hills reached the minimum requirement of 25 degrees imposed by the law. The highest average slopes were found in hill 3 (21.77º) and hill 15 (22.03°).

Even if the minimum size of the watershed for the Morro da Cruz massif is reduced, the criteria established by the current law (Native Vegetation Protection Law) do not allow for any level of protection for its summits (peaks). Although the hills in this massif reach significant heights (about 280 m) and many sectors of its slopes have steep degrees, none of the hilltops in the area were protected by this law. The law stipulates that a hilltop must have a height greater than 100 meters and an average slope above 25° in order to be protected.

Conclusions

The use of the Jurerê and Morro da Cruz massifs as case studies shows that, in a small geographical area with relatively simple geology, two distinct landforms exist. These landforms consist of ridge lines, isolated mounds, and hill peaks that exhibit varying characteristics. There is a need for further studies that address the mapping of hilltop PPAs to different structural reliefs present in Brazil. This will contribute to the determination of criteria that are better suited to regional geological-geomorphological realities. There is also little discussion of the fact that it is uncommon to have a single isolated hill-shaped as provided by law. Instead, undulating terrains in the form of massifs, mountains, or plateaus are more prevalent, where multiple summits (peaks) can be observed.

It was also evident that the minimum watershed size selected in the methodology for defining ridges lines and hills in relief compartments of massifs interferes with the size of hilltop PPAs according to the parameters of Conama Resolution No. 303/2002. With a smaller minimum watershed size, the number of hulls and peaks identified in the massifs increases, resulting in closer proximity between these peaks. This make the criterion of ridge lines is adopted to locate the PPAs. When using this criterion for ridge lines, the PPA will be defined by the upper third of the hill with the lowest height among the set of hills that form the ridge line. This provides enhanced protection for the summits of massifs, ridges, or plateaus with dissected topography.

According to the findings of this study, the loss of protected areas as hilltop PPAs in the studied massifs can be observed by comparing the criteria outlined in the Native Vegetation Protection Law with those specified in the repealed Forest Code and Conama Resolution No. 303/2002. This fact can promote urban expansion towards the hilltops of the crystalline massifs of Florianópolis. This expansion can lead to a decrease in the protection of native vegetation, increased soil sealing, and a reduction in aquifer recharge water. This compromises springs and rivers, among other environmental issues. The occupation of the upper third of the massifs can also result in the creation of high-risk areas due to the occurrence of floods and landslides.

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Marina Pinho Bernardes: Subject-matter research, data analysis and discussion of results.

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Article editor:

Fernando Villela

Received on: Jan. 05, 2022
Approved on: Apr. 28, 2023