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The Configuration of Forest Cover in Ribeirão Preto: A Diagnosis of Brazil's Forest Code Implementation

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Abstract: The fragmentation of forests is a consequence of human activities that intensively change the natural landscapes. In Brazil, there is a long-standing legal framework for native vegetation protection, called Forest Code. The last update is from 2012. The revisions incorporated in this restructured code (Law No. 12,651/12) encompassed new rules, rights and obligations for adequate land use management of productive systems and for environmental conservation and protection. An example of a protective measure was the creation of a Legal Reserve inside the rural properties and Areas of Permanent Protection around the watercourses. This study explored the effects of implementing the new code on the spatial and temporal evolution of forest cover fragmentation since the legal changes were set up. In that context, the area, perimeter and shape (circularity index) of forest fragments, as well as the buffer strips along watercourses, were assessed from 2010 to 2016 within the municipality of Ribeirão Preto, São Paulo state, Brazil. The assessment resorted to remote sensing techniques and visual inspection of orbital images. It was clear from the results that forest patches became more abundant but smaller, more dispersed and elongated, and that this route to fragmentation was hinged on a chaotic expansion of urban and agricultural areas. Important edge effects were anticipated from these results. The area numbers revealed that Ribeirão Preto was 7.95% covered with forest fragments in 2010, while this percentage rose to 8.03% in 2013 and reached 8.35% in 2016. Most of this increase occurred within a 30-meter wide buffer along the watercourses. This was a positive outcome. However, the numbers also revealed that forested areas smaller than 51 hectares increased from 71% in 2010 to 73% in 2016. The conclusions were that implementation of Law No. 12,651/12 is leading to an increase of forestland, but not yet promoting sustainability, namely through improved connectivity among fragments for reduction of edge effects and provision ecosystem services.

Keywords: land use policy; environmental law; sustainability; ecosystem services; Brazilian forest code; forest fragmentation; landscape ecology

1. Introduction

The changes to natural landscapes and the loss of forest cover are important causes of environmental imbalances, oftentimes with irreversible consequences to the quality of life standards and the availability of ecosystem services [1–5]. The maintenance of ecosystem functions has been related to specific occupation standards in some research. The data analyses described the negative effects of forest fragmentation as well as the benefits of forest conservation to the adjustment of hydric flows, carbon supply, biodiversity and the ecologic and climatic equilibrium on Earth [6–11]. Therefore, the maintenance of environmental balance depends on the preservation of forest ecosystems. To attain the goal, however, it is mandatory to decrease the loss of forest edge structure in farming and urban landscapes, among other initiatives [12–15].

In the modern world, the utopia of balanced landscapes requires the set-up of trade-offs between maintenance of ecosystem services and socio-economic development [16–19]. Without these trade-offs, the conversion of forest cover into anthropic land is likely to cause environmental damage, with generalized disruption of ecosystem functions and services [20–23]. In the Brazilian territory, the competition between conservation of native vegetation and agro-industrial activities has caused deforestation [24–26]. Frequently, the competition evolves to severe land use conflicts, because the expansion of productive areas reduces the system's capacity to conserve vital services, namely those related to water resources in river basins [27–31].

In a scenario of land competition and conflicts, the set-up of policies, rules, rights and obligations is extremely important to accomplish a sustainable zoning of land use in the rural areas where forest cover is ample. However, the implementation of an effective framework is challenging because the share of private properties where the breakdown of forest cover occurs is vast and the owners of these lands are seldom sensitive to environmental issues [32–35]. This is particularly evident in Brazil where the routes to keep the benefits of an ecosystem at the center of agricultural productivity or urban development diverge considerably between the economic and conservationist spheres. The elaboration of Forest Codes aimed to delineate a balance between these two interests [36,37]. The control of deforestation through Forest Code enforcement should help protecting native vegetation within the private lands.

The Brazilian Forest Code represents an assemblage of laws to regulate land uses, forest cover resources and other types of vegetation in the territory. The first code was instituted in 1934 and comprised important measures for the protection of forests, considering the enormous deforestation resulting from the ongoing countless and extensive coffee, cocoa and sugar cane plantations. Three decades later, Law No. 4771/65 revoked the previous code, imposing more strict measures to protect forests from the contemporary industrialization period. However, revisions to this new code were controversial because they allowed agricultural activities in environmentally sensitive and previously protected areas [38,39]. In 2012, following an intense discussion at the National Congress, a new forest code (Law No. 12,651/12) replaced the 1965 code. Besides the definition of rules for the protection and exploration of forests, the new law instituted a special protection for specific areas, namely for the Areas of Permanent Protection (APP) and the Legal Reserve (LR). The APPs correspond to buffers of forest cover delineated along the watercourses. The LR gathers a percentage of each rural property. This new protective measure was disruptive but also essential to the supply of ecosystem services.

The implementation of Law No. 12,651/12 produced impacts on vegetation cover that have been mentioned in several studies [38,40–43]. The law defined Areas of Permanent Protection delineated along the watercourses to work as environmental buffer, with predefined widths. The Legal Reserve was also defined as a percentage of a rural property that must be allocated to sustainable economic land uses. However, there are still information gaps concerning the composition, pattern and wood coverage in the watersheds, and about the environmental quality of forest remnants. It is therefore vital to make a comprehensive and updated diagnosis on the balance between economic activity and environmental protection, to verify how effective this vital law is. It is worth noting that presently, Brazil's natural vegetation cover is more than half (53%), located on private lands [38]. Considering the intensive conversion of native forest cover into agriculture in these lands, Brazil's environmental legislation should be an instrument to protect the native forest ecosystems and regulate the land use and land cover areas inside rural properties.

This study aims to analyze the forestry areas and to provide new insights about the implementation of Law No. 12,651/12, focusing on patterns, shape evolution, dimension and spatial distribution of native forest remnants. The assessment of forest fragmentation resorted to metrics of dimension and form. Satellite images from 2010 to 2016 were used to identify and monitor the areas where native forest cover occurs and to outline the forest fragments [44,45].

The research occurred in the administrative and political unit of Ribeirão Preto. This municipality encompasses an important agro-industrial center of São Paulo state (Brazil). In this region, the planting and processing of sugar cane is a dominant economic activity. The cultivation of sugar cane has replaced most areas previously occupied by other agricultural crops, such as coffee or citrus. Before that, the region was highly modified by the conversion of natural vegetation into agricultural areas. Presently, the forest remnants spread inside private rural properties account for 70% of Ribeirão Preto's territory. The region also encompasses the phytogeographic domains of Atlantic Forest and Cerrado where the Semi-Deciduous Seasonal Forest and Savanna formations prevail, which were recognized for their high endemism and diversity [46].

2. Materials and Methods

2.1. Study Area

The Ribeirão Preto municipality is located in the Northeast of São Paulo state, Southeast of Brazil, covering an area of 650,916 km^2 centered on the geographic coordinates of latitude—21°10′30″ S and longitude—47°48′38″ W (Figure 1). The geological units belong to the São Bento Group, comprising the General Mountain, Botucatu and, to a smaller extent, the Pirambóia formations. The main soil units are Red Latosol, Dark-Red Latosol and Litholic. The relief is undulated to strongly undulated and rolling, while the altitudes in the region vary from 50 to 800 m. The climate is tropical semi-moist, according to the Köppen-Geiger classification. The natural vegetation cover is Atlantic Forest, composed of seasonal semi-deciduous to non-deciduous forest [47].

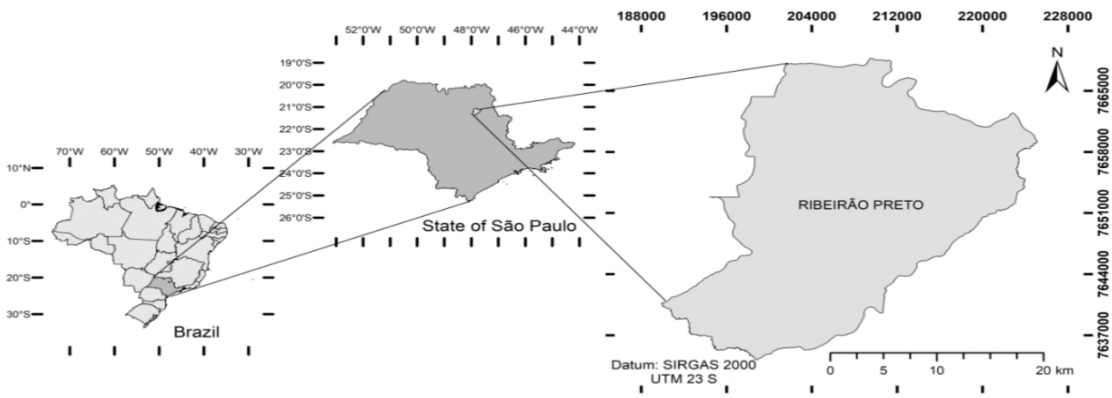

Figure 1. Geographic location of the political and administrative unit of Ribeirão Preto (São Paulo state, Brazil).

2.2. Data Collection and Analysis

The gathering of information and data on the spatial and temporal distribution of forest cover in the study area comprised visual interpretation of orbital images and remote sensing techniques. The images were from Google Earth Pro. This platform is progressively more used in scientific studies that require remote sensed data, as documented in a recent review paper [48], and therefore was considered adequate for the present work. Google Earth complements other sources of Earth images widely used in ecology studies [49–51]. The images refer to high-resolution scenes captured in 2010, 2013 and 2016. The interpretation and photogrammetry of these scenes comprehended the collection of data on color, tonality, shape, size, standard, texture, association and shadow, and accounted for phenological differences between the land uses and cover over seasons [52–56]. This information allowed the identification of forest fragments and their delineation through manual vectorization. Following this stage, the polygons representing the forest fragments were exported to ArcGIS Desktop software, version 10.5, of ESRI (https://www.esri.com) for quantitative assessments and production of thematic maps (e.g., Figure 2 below).

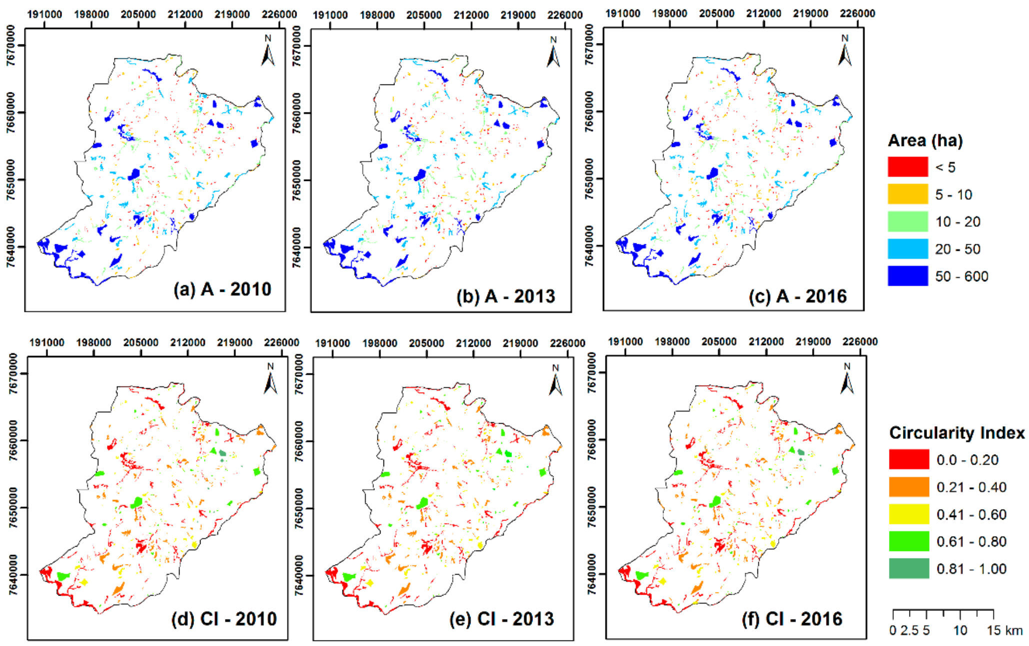

Figure 2. Spatial distribution of forest fragments in the political and administrative unit of Ribeirão Preto in 2010, 2013 and 2016. The upper panels (**a**–**c**) are graduated according to area, the lower (**d**–**f**) according to circularity index.

The measurements performed on ArcGIS Desktop comprehended the calculation of area, perimeter and the circularity index of each polygon representing a forest stand. The ArcGIS Desktop software includes internal functions for the calculation of area (A) and perimeter (P), while the circularity index was computed from A and P using the "Field Calculator" tool based on the equation appearing in Chaturvedi [57]:

$$CI = (40{,}000.\pi.A.)/P^2 \quad (1)$$

where:

CI = Circularity Index; A = Area (1 hm^2); P = Perimeter (m).

The CI ranges from 1 (a perfect circle) to 0 (an irregular shape). Therefore, the index describes the shape of a fragment concerning its resemblance to a circular shape. The closer to the circular outline, the more regular the shape is. Regularity assures larger distances from the edges in relation to the center of the fragment. Consequently, values closer to 1 should indicate enhanced protection to nuclear areas of the fragments. The fragment's shape together with the area determines the final consequence of a possible external disturbance to the habitat [58]. It is worth recalling, in this regard, that an association between a reduced area and an irregular shape decreases the nuclear area of forest fragments, making them more prone to edge effects.

The forestland was also analyzed along the drainage network. The purpose was to quantify the share of forests within riparian strips defined alongside the perennial and seasonal watercourses of Ribeirão Preto, and verify the impact of forest code implementation in the Areas of Permanent Protection. The extraction of water lines in shapefile format within this municipality was accomplished through automatic interpretation of a 30 × 30 m Digital Elevation Model (in raster format), using the ArcHydro extension of ArcGIS 10.5. Four buffers were drawn around the drainage network at predefined distances. The buffer widths were 30, 50, 100 and 250 m wide.

3. Results

The spatial and temporal distributions of forest cover in the Ribeirão Preto municipality are illustrated in Figure 2. The number of forest fragments increased from 393 in 2010 to 413 and 44 in 2013 and 2016 respectively. Over the study period from 2010 to 2016, the fragments increased to 13.2%. The total forested area also increased from 5185.63 ha to 5224.53 ha and subsequently to 5432.32 ha, but the percentage of increase was much smaller (just 4.8%). This implies a decrease in the mean area of forest fragments. A similar conclusion could be attained from analysis of forest stand perimeters, which increased from 888,645 m to 906,010 m and 957,358 m, i.e., solely 7.7% in the 2010–2016 period.

The distribution of forest fragments per area and perimeter classes is presented in Table 1. The fragments smaller than 5 ha dominated the landscape, as they represented 54%, 56% and 56% of all forest stands in 2010, 2013 and 2016, respectively (see also Figure 2a–c). This class showed a visible and continuous increase in the number of spots within the studied timeframe (it has raised 37 elements). The fragments larger than 5 ha and smaller than 20 ha were the second dominating group with shares of 30%, 29% and 30% in the same years. This group also showed an increase in the number of spots (12), but the increment occurred mostly from 2013 to 2016 (11). The medium (80–200 ha), large (80–200 ha) and very large (>200 ha) classes all together, represented 16%, 15% and 14% of all fragments and kept the number of elements practically unchanged throughout the studied period (61 in 2010 and 2013; 63 in 2016).

The evolutionary pattern observed for fragment area can be reproduced for perimeter as well. In 2010, the number of forest fragments in the class <1000 m was 165. In 2013, this number raised to 180 (15 more spots) and in 2016 to 192 (more 12). Thus, in total, the group of smaller fragments was 27 larger in 2016 relative to 2010. As one looks to the classes of larger perimeter (1000–1500 m, 1500–2000 m, etc.), the growth in the number of fragments became more steady, namely more 7, 10, 5, 1, 1, and 1 elements, respectively.

The distribution of forest fragments per classes of circularity index (CI) is described in Table 2 and illustrated in Figure 2d–f. In 2010, the elongated patches were dominant, namely the <0.17 (79 spots) and 0.17–0.5 (186) groups. The three intermediate classes, which span the 0.5 < CI < 0.8 range, assembled 117 of all fragments, while the most rounded patches (CI = 0.8–1.0) formed a ground of just 11 elements. In 2016, the number of fragments in the elongated classes was substantially more than in 2010, especially those included in the 0.17–0.5 class that increased to 219 patches (33 more relative to 2010). The other classes also raised the number of fragments, but modestly (between 3 and 6), except the class 0.8–1.0 that kept the initial number of patches (11). If one centers the analysis on relative increases (percentages), it is clear that class 0.17–0.5 increased, while most of the other classes became less represented in the transition from 2010 to 2016. Overall, the results point to the spreading of forest fragmentation. This process has raised the number of small and elongated fragments, with potential aggravation of edge effects related to expansion of urban areas and agriculture surrounding the forested areas of Ribeirão Preto municipality.

Table 1. Distribution of forest fragments per area (ha) and perimeter (m) classes in the political and administrative unit of Ribeirão Preto in the years of 2010, 2013 and 2016. Symbols: Count—number of forest fragments; A—Total area of forest fragments, FA—Average area of forest fragments.

Forest Fragments	**2010**					**2013**					**2016**				
	Count	**%**	**A (hm^2)**	**%**	**FA (ha)**	**Count**	**%**	**A (hm^2)**	**%**	**FA (ha)**	**Count**	**%**	**A (hm^2)**	**%**	**FA (ha)**
Classes of area (hm^2)															
<5	214	54	462.6	9	2.2	233	56	494.7	9	2.1	251	56	539.5	10	2.1
5–10	66	17	476.1	9	7.2	67	16	482.9	9	7.2	75	17	542.7	10	7.2
10–20	52	13	712.1	14	13.7	52	13	712.1	14	13.7	56	13	761.2	14	13.6
20–80	49	12	1691.7	33	34.5	49	12	1691.7	32	34.5	51	11	1745.9	32	34.2
80–200	11	3	1254.6	24	114.1	11	3	1254.6	24	114.1	11	2	1254.6	23	114.1
>200	1	0	588.4	11	588.4	1	0	588.4	11	588.4	1	0	588.4	11	588.4
Total	393	100	5185.6	100	14.21	413	100	5224.5	100	13.4	445	100	5432.3	100	12.2
Classes of perimeter (m)															
<1000	165	42	105,704	6	638.8	180	44	114,562	6	636.5	192	43	123,514	6	643.3
1000–1500	63	16	77,712	6	1233.5	65	16	80,181	6	1233.6	70	16	86,140	6	1230.57
1500–2000	31	8	54,317	5	1752.2	33	8	57,840	5	1752.7	41	9	71,607	6	1746.95
2000–2500	25	6	56,846	5	2273.8	26	6	59,061	5	2271.6	30	7	68,440	5	2281.33
2500–3500	35	9	103,447	13	2955.6	35	8	103,447	13	2955.6	36	8	106,123	12	2947.86
3500–5500	50	13	215,740	25	4314.8	50	12	215,740	24	4314.8	51	11	220,279	28	4319.2
5500–50,000	24	6	275,179	41	11,465.8	24	6	275,179	41	11,465.8	25	6	281,255	38	11,250.2
Total	393	100	888,945	100	2262	413	100	906,010	100	2193	445	100	957,358	100	2151

Table 2. Distribution of forest fragments per class of circularity index (CI) in the political and administrative unit of Ribeirão Preto in the years of 2010, 2013 and 2016.

CI Classes	2010		2013		2016	
	Count	%	Count	%	Count	%
<0.17	79	20.1	82	19.9	85	19.1
0.17–0.5	186	47.3	195	47.2	219	49.2
0.5–0.6	41	10.4	42	10.2	44	9.9
0.6–0.7	40	10.2	45	10.9	47	10.6
0.7–0.8	36	9.2	38	9.2	39	8.8
0.8–1.0	11	2.8	11	2.7	11	2.5
Total	393	100	413	100	445	100

The spatial distribution of forested areas within buffers of predefined distance alongside the watercourses (30, 50, 100 and 250 m wide) is illustrated in Figure 3. The increase observed in the 2010–2016 period is evident for all buffers. It ranged from 2% in the smaller buffers (from 19 to 21% in the 30 m buffer; from 17 to 19% in the 50 m buffer) to 1% in the larger buffers (from 13 to 14% in the 100 m buffer; from 8 to 9% in the 250 m buffer). The figure also shows that as the buffer widens, the share of forests decreases, which means that the forest occupation becomes sparser.

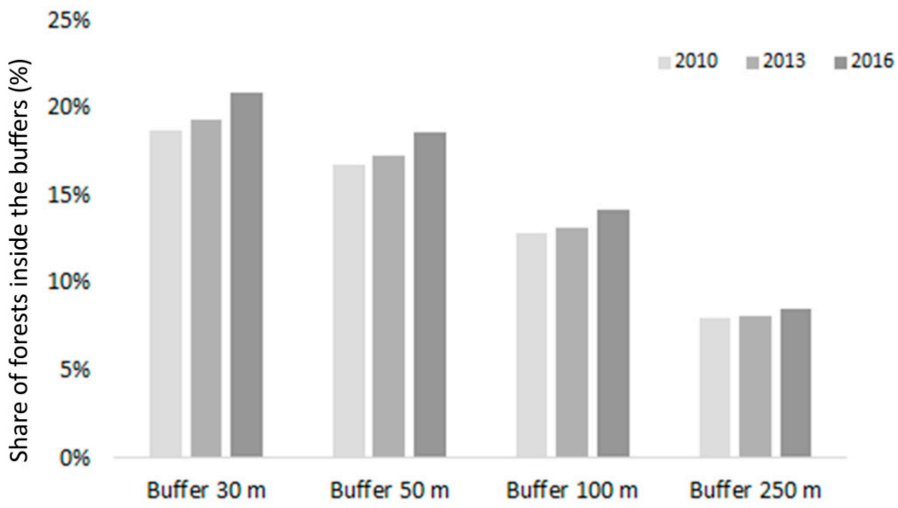

Figure 3. Distribution of forest fragments within buffers of predefined width defined along the watercourses of Ribeirão Preto in 2010, 2013 and 2016.

4. Discussion

The fragmentation of forest cover was evident in the Ribeirão Preto municipality in 2010 and the pattern has not changed in the 2010–2016 period. Within this timeframe, the number of small and elongated patches has increased and amplified the fragmentation. However, the reforestation of riparian areas has improved. Overall, the implementation of Brazil's new Forest Code was apparently effective in the (re)build of APPs (Areas of Permanent Protection), but relatively ineffective in the development of an ecologically sustainable Legal Reserve. The process of fragmentation hinged on the development of agricultural productive systems, the human infrastructures derived therefrom, and the urban expansion. The sugar cane culture represented 57% of Ribeirão Preto's administrative region in 2016 [59]. The expansion of sugar cane farming in this region can explain the standard of fragmentation and the irregularity of the fragment's shape, because the agrarian activity was set up in large areas previously occupied by native vegetation. The expansion of agriculture and urban areas is typically very damaging to forest health and habitat quality. Ultimately, it can cause permanent negative effects, endangering the ecosystem's sustainability [60]. In the Ribeirão Preto municipality, as common practice, the farming expansion occupied the areas of low slope, because machinery can easily move across these areas. A similar spreading was observed by Adami et al. [61], who studied the farming expansion and Atlantic Rainforest patches in São Paulo state.

The traditional fragmentation in the Ribeirão Preto municipality is mostly of small areas. The process of fragmentation observed in this territory has also occurred in the Northeast region of São Paulo State [62,63], where the surface is 13.70% occupied with fragments of Atlantic Forest. The report on the growing number of patches with a small circularity index (Table 2) exposes how inefficient the enforcement of Brazil's Forest Code was until 2016. These patches are prone to edge effects and a source of concern to public administrators [64]. The small ratios of area/perimeter that typify forest fragments with small circulation index increase the contact of natural vegetation with other anthropic environments. This is likely to trigger various negative effects on wildlife quality and biodiversity because of a potential pollution increase inside the fragment, among other disturbances. The edge effects also change the growth conditions of vegetation in the fragment centers, because of drastic changes in temperature, moisture, light and wind, which in turn decrease the biomass and change the nutrient cycles. The effects are more important in the small and more isolated patches [4,6,7,9,11]. They increase as time goes by and ultimately compromise the fragments' sustainability [65]. Therefore, it is urgent to enforce the Forest Code more strictly in the Ribeirão Preto municipality, through implementation or imposition of restoration, protection and connectivity initiatives that could increase forest fragment circularity and improve biodiversity as well as the viability of ecosystem services in the sequel.

The implementation of harmonious productive models would help in improving circularity and the connectivity among forest patches [66]. The agroforestry systems (AFSs) are a good example of a harmonious productive model [67]. The Brazilian law allows the development of AFSs in the Legal Reserve, meaning that exploration of these areas can occur under a sustainable model where partial management and partial maintenance of vegetation coexist. Eventually, the implementation of AFSs would alleviate the pressure on deforestation that has increased, along with the pressure on sugar cane and ethanol production used for fuel supply. Besides the implementation of AFSs, other initiatives are also thought to reduce edge effects around small and irregular forest fragments. For example, the damping area around the most irregular fragments could be raised [68,69]. The recovering of patches could also occur through natural regeneration. According to Ghazoul and Chazdon [70], the processes of natural recovery can improve the landscape heterogeneousness, besides reducing the edge effects. Taken all together, these conservationist initiatives would help in building a sustainable Legal Reserve in the region.

The enforcement of Brazil's new Forest Code has resulted in the expansion of forest cover inside the APPs [71]. The present study confirms this positive outcome in the Ribeirão Preto municipality within the studied period. For all buffers, but especially the 30 to 50 m wide, the forest fragments and their area increased around the watercourses. The legal framework about the APPs comprises an ample set of rules related to land use and cover organization in space and time. The economic activities close to these areas should attend these rules and precisely define how the landowners can manage their licenses to work. The discussion about environmental management in connection with neighboring cropping and urban communities is of paramount importance in this regard. For example, according to the set rules, forests should cover the APPs completely, but 60% of these areas do not respect the regulations. On the other hand, the patches of Legal Reserve located in the rural properties should be connected to each other and extend to the APPs, forming ecological corridors. However, many properties violate this rule. In cases where the respect for the set laws is lacking, landowners ought to repair the situation.

Despite the disrespect of many rules, the implementation of Brazil's Forest Code has produced some good results, which are subtle so far. Eventually, a closer monitoring (e.g., through remote sensing devices such as drones) of private reforestation plans, coupled with the implementation of other practical instruments (e.g., "polluter pays principle"), would help in improving further the riverine ecosystems and their services. The approach of involving legal and administrative authorities, landowners, environmental groups and the local community in a collective decision-making experience would produce the best and enduring results, but may be a utopia. At this point, it is worth recalling Article 225º of the Brazilian Constitution that renders everyone "the right to an ecologically balanced environment, which is an asset of common use and essential to a healthy quality of life, and both the Government and the community shall have the duty to defend and preserve it for present and future generations".

The extensive response of land use and cover to legal constraints was already observed in many regions around the globe, namely in the Benin Republic after the implementation of law 1–2013 [72]. We do consider the possibility of accomplishing this goal in Brazil. However, there are some prerequisites for success. The national policies and laws should supply the society with a coherent set of strategies and rules to manage the APPs and the LRs. In addition, they should define goals and deadlines for the recovery of damaged APPs and LRs, in keeping with the rules set out in the Brazilian Forest Code. To be successful in this enterprise, the regulations for implementing the Forest Code should become practical and intuitive for all intervenors, namely landowners. In this regard, they need to describe how, when and where the interested landowners must manage their areas for a sustainable forestland.

5. Conclusions

The new Forest Code (Brazilian Law No. 12,651/12) was established in 2012 and implemented since then. The results of a remote sensed assessment of area, perimeter and circularity index allowed the checking of forest fragmentation in Ribeirão Preto municipality from 2010 to 2016. The forests were fragmented in 2010, because the number of small and elongated patches were dominant in the landscape. In 2016, the situation improved because the forest cover increased. However, the dominance of elongated patches persisted. A promising outcome from the diagnosis was that reforestation around the watercourses (Areas of Permanent Protection) improved. Overall, the implementation of Brazil's new Forest Code in the studied period was positive but not as active as should be, and therefore requires a more strict enforcement in the future.

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