https://doi.org/10.22478/ufpb.1981-1268.2022v16n2.61986

Assessing the success of forest restoration based on landscape analysis

Allan Rodrigo Nunho dos Reis[1*], Daniela Biondi[1], Ana Paula Dalla Corte[1], Antonio Carlos Batista[1], Fabiano Peixoto Freiman[2], Eduardo Campanhã Ribas[1], Iran Jorge Corrêa Lopes[1], Jennifer Viezzer[1]

1 Programa de Pós-Graduação em Engenharia Florestal, Universidade Federal do Paraná. Avenida Prefeito Lothário Meissner, 632, Jardim Botânico, Curitiba, Paraná – Brasil. 80210-170.
2 Departamento de Engenharia de Transportes e Geodésia. Universidade Federal da Bahia. Rua Professor Aristides Novis, 02, Federação, Salvador, Bahia – Brasil. 40210-630.
*Autor para correspondência: allan.nunho@gmail.com

Recebido em 24 de janeiro de 2022.
Aceito em 10 de setembro de 2022.
Publicado em 23 de setembro de 2022.

Abstract - Recognition of landscape configuration is essential to define priority sites most likely to succeed in forest restoration. The research aimed to reduce uncertainties regarding the feasibility of ecological restoration processes by applying landscape metrics to support priority areas for restoration in three watersheds located in the northwest region of the state of Paraná, Brazil. A temporal analysis of the landscape was performed for the years 1985, 1996, 2007, and 2018. Seven land use and land coverage categories were proposed and seven landscape metrics were calculated to assess the configuration using the Fragstats® software, and an assessment of restoration success using GoFor® software. The studied area was divided into four priority levels: low, medium, high, and very high probability of restoration success. The landscape matrix was composed of pastures and agriculture, which corresponded to almost 90% of the area. There has been a considerable increase in forest coverage over the years due to commercial plantations and the recovery of Permanent Preservation Areas (APP). Approximately 12.6 percent of the landscape has the potential to be restored if restoration efforts are allocated to areas with the highest potential for restoration success.

Keywords: Ecological restoration. Landscape ecology. Seasonal Semideciduous Forest.

Avaliando o sucesso da restauração florestal com base na análise da paisagem

Resumo - O reconhecimento da configuração da paisagem é essencial para definir os locais prioritários com maior probabilidade de sucesso para a restauração florestal. A pesquisa teve como objetivo reduzir as incertezas quanto à viabilidade dos processos de restauração ecológica aplicando métricas de paisagem para apoiar as áreas prioritárias para restauração em três bacias hidrográficas localizadas na região noroeste do estado do Paraná, Brasil. Uma análise temporal da paisagem foi executada para os anos de 1985, 1996, 2007 e 2018. Sete categorias de uso e cobertura do solo foram propostas e sete métricas de paisagem foram calculadas para avaliar a configuração usando o *software* Fragstats®, e uma análise de sucesso de restauração usando o *software* GoFor®. A área estudada foi dividida em quatro níveis de prioridade: baixa, média, alta e muito alta probabilidade de sucesso da restauração. A matriz paisagística foi composta por pastagens e agricultura, que correspondiam a quase 90% da área. Houve um aumento considerável da cobertura florestal ao longo dos anos devido aos plantios comerciais e à recuperação de Áreas de Preservação Permanente (APP). Aproximadamente 12,6% da paisagem tem potencial para ser recuperada se os esforços de restauração forem alocados em áreas com maior potencial de sucesso de restauração.

Palavras-chave: Ecologia da paisagem. Floresta Estacional Semidecidual. Restauração ecológica.

Evaluación del éxito de la restauración forestal basada en el análisis del paisaje

Resumen - El reconocimiento de la configuración del paisaje es esencial para definir los sitios prioritarios con mayor probabilidad de éxito para la restauración forestal. La investigación tuvo como objetivo reducir las incertidumbres sobre la factibilidad de los procesos de restauración ecológica mediante la aplicación de métricas de paisaje para apoyar áreas prioritarias para la restauración en tres cuencas hidrográficas ubicadas en la región noroeste del estado de Paraná, Brasil. Se realizó un análisis temporal del paisaje para los años 1985, 1996, 2007 y 2018. Se propusieron siete categorías de uso y cobertura del suelo y se calcularon siete métricas del paisaje para evaluar la configuración utilizando el software Fragstats®, y un análisis del éxito de la restauración mediante el software GoFor®. El área de estudio se dividió en cuatro niveles de prioridad: baja, media, alta y muy alta probabilidad de éxito en la restauración. La matriz del paisaje estaba compuesta por pastos y agricultura, que correspondía a casi el 90% del área. Ha habido un aumento considerable de la cobertura forestal a lo largo de los años debido a las plantaciones comerciales y la recuperación de Áreas de Preservación Permanente (APP). Aproximadamente el 12,6% del paisaje tiene el potencial de ser restaurado si los esfuerzos de restauración se asignan a áreas con el mayor potencial para el éxito de la restauración.

Palabras-clave: Bosque Semideciduo Estacional. Ecología del paisaje. Restauración ecológica.

Introduction

Strategies to enhance ecosystem restoration became essential due to high forest degradation and climate change (Crouzeilles et al. 2019). Based on this issue, the United Nations (UN) declared the period between 2021 and 2030 as the Decade of Restoration (UN 2019). Among these restoration efforts, growing green areas may enhance and accelerate the recovery of original characteristics of a disturbed environment, contributing to the maintenance of ecosystem services (Ibáñez and Rodríguez 2020). Nevertheless, the success of ecological restoration depends on planning according to scale, landscape, social context, restoration goals, and combinations of planted species (Stanturf et al.

2014; Crouzeilles et al. 2019; Ibáñez and Rodríguez 2020), in addition to the characteristics of forest fragments such as size and shape, with the largest area and the most regular format being preferred.

Combined, landscape ecology and ecological restoration are important tools for achieving ecosystem restoration, due to the relationships between landscape and ecological processes (Bell et al. 1997; Stanturf et al. 2014). While former studies considered spatial patterns and their relations to ecological and environmental processes, more recent ones, such as Crouzeilles et al. (2019) and Abhilash (2021), consider human intervention as necessary to restore degraded ecosystems. Therefore, the knowledge of landscape dynamics provides information that may help in the diagnosis of current and future problems and foster interventions that can favor natural regeneration, ecosystem sustainability, and its functionality (Calegari et al. 2010; Crouzeilles et al. 2019).

The Brazilian Atlantic Forest, considered a biodiversity hotspot (Myers et al. 2000), is one of the most degraded areas in the world, which justifies a higher concentration of restoration efforts. This hotspot is an association of different ecosystems, such as the Semi-deciduous Seasonal Forest (SSF). Oliveira and Engel (2017) found that most research on Atlantic Forest's restoration from 1980 to 2009 has been conducted in the SSF ecosystem, mainly in the Southeast and South regions of Brazil. However, only 3.7 percent of them considered landscape dynamics to support forest restoration (Oliveira and Engel 2017).

During the twentieth century, the area covered by the SSF has suffered an intense decrease from 46.68 percent to 3.97 percent in the state of Paraná mainly as a result of land use and land cover changes for livestock and agricultural purposes (IPARDES 2017; Maack 2017). A new landscape emerged with aspects of degradation, which led to changes in ecological and water dynamics as well as soil degradation and deep erosive processes, such as gullies (Maack 2017). Thus, the northwestern region of Paraná, where the SSF naturally occurred, was identified as one of the priority areas for forest restoration in the Atlantic Forest by Melo et al. (2013), due to intense landscape degradation in the last decades.

To achieve restoration success, it is necessary to know how, when, and where to intervene (Ferrari et al. 2021). However, knowing exactly where to invest in restoration efforts is challenging. The uncertainties related to the success of biodiversity recovery in degraded areas can diminish the investor's confidence in restoration projects, which may undermine long-term ecological sustainability and functionality (Crouzeilles et al. 2019).

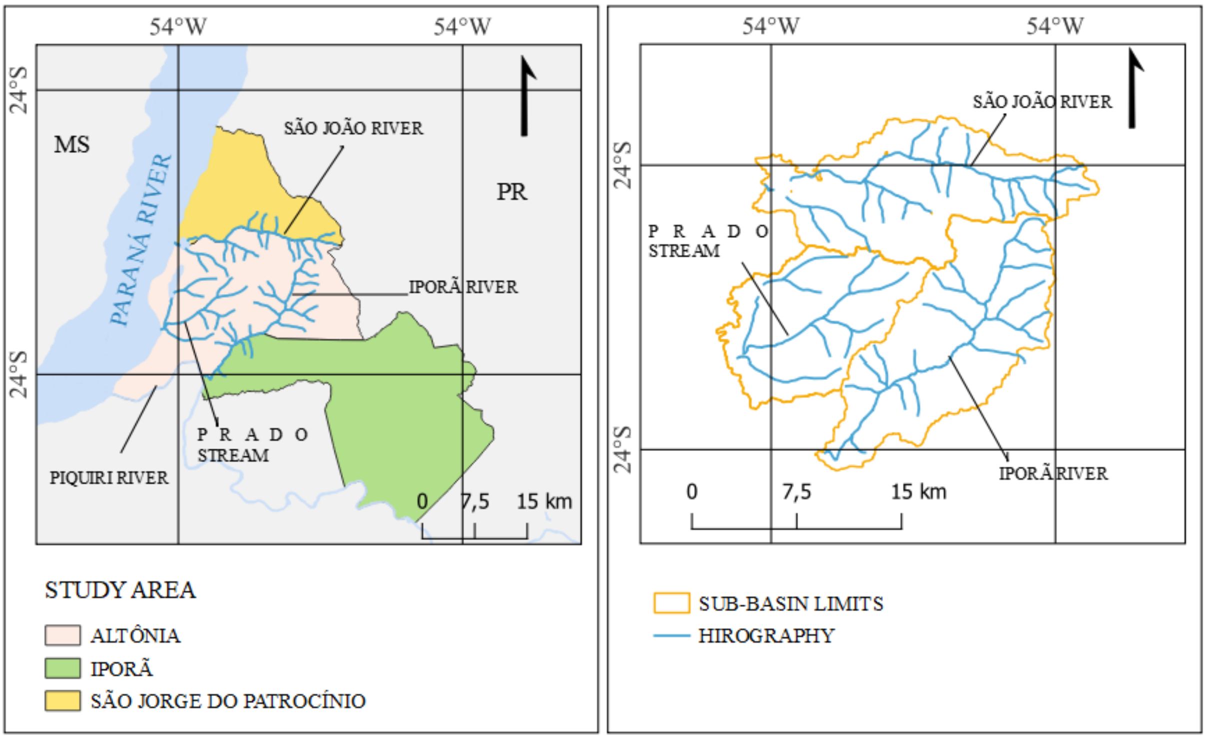
To address these uncertainties, the influence of the landscape matrix on the effectiveness of ecological restoration should be considered (Crouzeilles and Curran 2016). This assessment can be performed using landscape metrics that demonstrate the spatial configuration and that can provide evidence about its environmental quality for forest restoration, related to the distribution of matrix, fragments, and corridors in the landscape (Bell et al. 1997). Associated with temporal analyzes, these metrics can provide better information about the level of environmental degradation, contributing to the success of the restoration process.

This study aimed to reduce the uncertainties regarding the viability of the processes by applying landscape metrics to support the priority areas for restoration in three watersheds located in the northwest region of the state of Paraná, Brazil.

Material and Methods

The target area comprehends three sub-basins – *Rio São João* (São João River), *Rio Iporã* (Iporã River), and *Ribeirão do Prado* (Prado Stream) – located in three different towns – respectively, São Jorge do Patrocínio, Altônia and Iporã – in the northwest region of the state of Paraná (PR), Brazil (23.70° S, 54.40° W, and 24.00° S, 53.76° W) (Figure 1). The area has 42,074 ha, of which 41.97 percent is covered by São João River's sub-basin, 37.56 percent by Iporã River's sub-basin and 20.47 percent by Prado Stream's sub-basin. The majority of the area is situated in Altônia (79.38 percent), while 8.75 percent is in Iporã, and 11.82 percent in São Jorge do Patrocínio. The sub-basins of São João River and the Prado Stream integrate the Paraná River basin, while the sub-basin of Iporã River is part of the Piquiri River basin.

Figure 1. The location of the sub-basins of São João River, Iporã River, and Prado Stream, PR, Brazil.



According to the Köppen-Geiger climate classification, the area is defined as Cfa (subtropical mesothermal) – warm temperature, fully humid, and with hot summers (Maack 2017). The rainfall is concentrated during the summer (from December to March), with no defined dry season, while the driest period occurs between May and September (Koproski et al. 2004). The average annual rainfall is 1,576 mm, the average annual temperature is 21.86 °C and the average annual relative humidity is 70.55 percent (Wrege and Fritzsons 2015).

Procedures

The temporal landscape analysis was performed using data from satellite images of the area in the years 1985, 1996, 2007, and 2018 provided by LANDSAT 5, 7, and 8 satellites, with a spatial resolution of 30 m. Such images are available on the MapBiomas platform, where maps have an 84.40 percent accuracy (MAPBIOMAS 2020) and use automated cloud processing available on the Google Earth Engine platform. The data available in the 2019 collection of the MapBiomas platform contains land use maps from 1985 (with records taken from Landsat 5) to 2019 (from Landsat 8). Such periods were chosen to cover 33 years of data available, resulting in a representative range of each decade.

Pre-processing was performed using the open-source software QGIS® 3.12.1 with the Geographic Resources Analysis Support System (GRASS GIS 7.8.2), as well as the Semi-Automatic Classification Plugin used to define classes of interest and the suitability of the classified rasters. For each year, land use and land cover were classified exclusively as agriculture, pasture, commercial forest, forest cover, non-forest vegetation cover, water, and urban.

Seven metrics (Table 1) were selected to compose the landscape assessment, which was calculated for each year considering the land use and land cover classification. Such metrics were chosen due to their representation of the landscape structure and configuration (Calegari et al. 2010; McGarigal 2015) and were calculated using the software Fragstats® 4.2.1 from 2015 (McGarigal 2015). The landscape matrix was represented by the element that occupies more than 50 percent of its total extension defined by the Relative Area Method (Forman and Godron 1986).

Table 1. Landscape metrics for the temporal analysis of the studied area.

Metric	Terminology and unit	Meaning	Interpretation
Total class area	CA > 0 (ha)	Sum of the area of fragments in each class	Higher values favor conservation, representing the largest coverage of the landscape by a class
Percentage of landscape	PLAND (%)	Percentage of the area occupied by a class in the landscape	A higher value indicates a greater representation of a class in the landscape
Number of patches	NP ≥ 1	Number of class fragments	A higher value indicates greater fragmentation of the landscape
Mean patch area	AREA_MN > 0 (ha)	The average area of all class fragments	Larger fragments tend to have greater diversity, as the species diversity depends on the dimensions of the forest fragments
Mean patch shape index	SHAPE_MN > 1	The average value of the shape index of the fragments of each class	Small values indicate a simple form, which is more regular and favors conservation
Mean Proximity Index	PROX_MN > 0	The average distance from/to the nearest forest fragment	The lower the value, the closer the fragments are
Connectivity	COHESION < 100 (%)	Physical connectivity between class fragments	Higher values favor gene flow between forest fragments

Source: Adapted from Calegari et al. (2010) and McGarigal (2015).

To select the target areas most likely to be successful in restoration, the software GoFor® (Ecological Restoration Uncertainty Assessment) 1.0.x, October 2019 (Sarmiento et al. 2019) was used. This software evaluates the probability of success of the forest restoration process and indicates which sites are more suitable for interventions that can foster forestry recovery. Such software was developed based on the research acquired by Crouzeilles et al. (2019). According to Sarmiento et al. (2019), GoFor® supports decision-making processes to maximize ecological gains. With GoFor®, the uncertainty of the forest restoration success is estimated based on geospatial analysis of data available in raster format, which contains classified representations of land use and land cover of the area. For this study, data from 2018 was analyzed.

The previously categorized input files were reclassified as forest, non-forest with restoration potential, and non-forest with no potential for restoration. Areas with agricultural and pasture were reclassified as restorable areas, while commercial forests, non-forest vegetation covers, water, and urban areas were reclassified as non-restorable. The forest class was used to calculate the probability of restoration success. Due to the source of propagating materials represented by the forest fragments, restoration efforts are more likely to be successful if they are applied in regions with a relevant number of these fragments in their surroundings (Sousa et al. 2017).

Associated with the spatial configuration file of land use and land cover, GoFor® considers the smallest size of existing forest fragments in the area and the maximum distance between them to estimate the uncertainty of the success of forest restoration (Sarmiento et al. 2019). This information, about the smallest size of forest fragments and maximum distance between them, was estimated based on the landscape metrics previously assessed and considering a perimeter area of 100 m around the forest fragments.

The ten classes of the probability of restoration success provided by GoFor® were classified into four levels: low (0.00–25.00 percent), medium (25.01–50.00 percent), high (50.01–75.00 percent), and very high (75.01–100.00 percent).

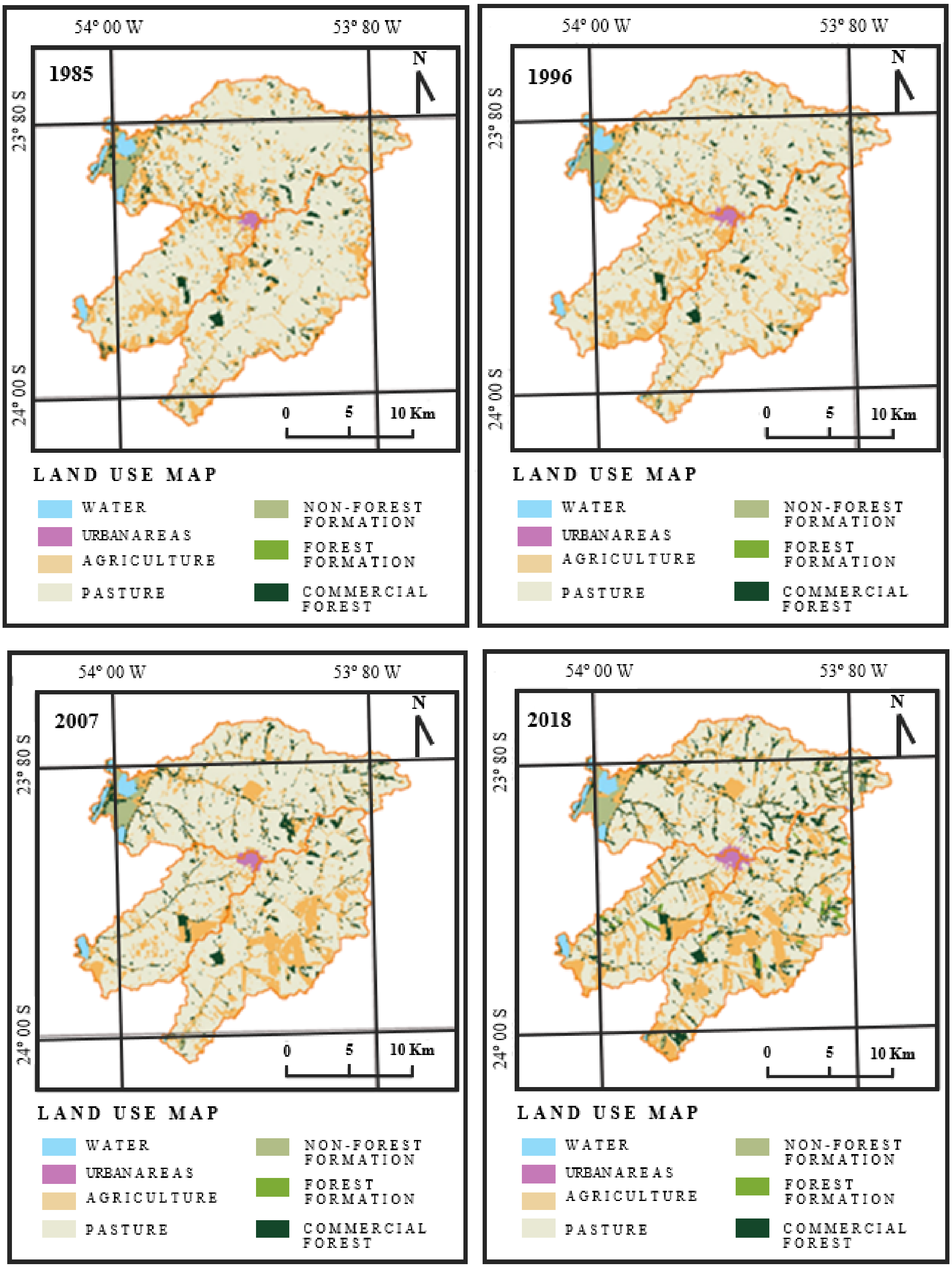
The data used to calculate the landscape metrics and the probability of restoration success has a spatial resolution of 30 m. Thus, the analyzes and results are relative to a scale of 1:150,000.

Results

The land use and land cover of the studied area are essentially pasture and agriculture. Thus, the landscape matrix corresponds to the pasture class, which occupied more than 70 percent of the landscape in 1985, 1996, and 2007, having a small decrease in 2018 and achieving nearly 60 percent due to the increase in agriculture, planted forests and forest formation. Combined, the pasture and agriculture classes correspond to approximately 90 percent of the landscape.

Although from 1985 to 2018 the areas with pasture were still predominant, agriculture and forest cover use increased (Figure 2). The first signs of planted forests occurred in 2007. The areas with non-forest vegetation cover and water remained essentially constant, varying from 1.46 percent in 1985 to 1.56 percent in 1996 in the case of non-forest vegetation, and from 1.67 percent in 1985 to 1.61 percent in 2007 in the case of the water class.

Figure 2. Temporal variation of the land use and land cover classes in the sub-basins of Rio São João, Ribeirão do Prado, and Rio Iporã, PR, Brazil.



The number of fragments in all analyzed classes increased from 1,942 in 1985 to 2,452 in 2018 and, on the other hand, the average fragment area decreased, from 285.53 ha in 1985 to 221.15 ha in 2018. There was a gradual area decrease in the pasture class, as the area of the agriculture and forest cover classes increased (Table 2). However, the pasture class had a small decrease in connectivity

(COHESION), indicating that the increase in agriculture and forest cover may have occurred in areas that used to be pasture.

Table 2. Landscape metrics for the land use and land cover classes of the studied area.

1985							
Class	**CA (ha)**	**PLAND (%)**	**NP**	**AREA_MN (ha)**	**SHAPE_ MN**	**PROX_ MN**	**COHESION (%)**
Agriculture	7,741.23	18.40	1,106	6.99	1.57	63.07	95.56
Pasture	31,007.54	73.70	168	184.57	1.39	38,759	99.96
Forest cover	1,837.71	4.37	573	3.21	1.42	5.16	87.99
Commercial forest	0	0	0	0	0	0	0
Water	702.60	1.67	44	15.97	1.40	8.12	96.33
Non-forest vegetation cover	614.76	1.46	48	12.81	1.45	63.84	96.58
Urban	185.95	0.44	3	61.99	1.73	307.07	97.77
1996							
Class	**CA (ha)**	**PLAND (%)**	**NP**	**AREA_MN (ha)**	**SHAPE_ MN**	**PROX_ MN**	**COHESION (%)**
Agriculture	8,168.42	19.41	1,201	6.80	1.60	63.75	95.42
Pasture	30,710.91	72.97	179	171.57	1.38	41,873	99.96
Forest cover	1,606.53	3.82	540	2.98	1.41	3.84	87.93
Commercial forest	0	0	0	0	0	0	0
Water	684.62	1.63	21	32.60	1.50	7.86	96.99
Non-forest vegetation cover	655.67	1.56	52	12.61	1.40	63.19	96.88
Urban	263.63	0.63	5	52.73	1.73	142.66	97.73
2007							
Class	**CA (ha)**	**PLAND (%)**	**NP**	**AREA_MN (ha)**	**SHAPE_ MN**	**PROX_ MN**	**COHESION (%)**
Agriculture	7,694.57	18.28	1,298	5.93	1.56	188.97	97.21
Pasture	30,228.33	71.82	121	249.82	1.57	27,696	99.94
Forest cover	2,614.85	6.21	551	4.75	1.56	12.24	91.87
Commercial forest	6.74	0.02	6	1.12	1.14	0.12	76.61

Water	678.24	1.61	25	27.13	1.45	12.67	96.81
Non-forest vegetation cover	618.44	1.47	46	13.44	1.43	26.36	96.91
Urban	248.62	0.60	7	35.52	1.29	2.87	97.95
				2018			
Class	**CA (ha)**	**PLAND (%)**	**NP**	**AREA_MN (ha)**	**SHAPE_ MN**	**PROX_ MN**	**COHESION (%)**
Agriculture	10,014.94	23.79	1,425	7.03	1.50	173.56	97.04
Pasture	26,129.42	62.07	204	128.09	1.65	7,881	99.04
Forest cover	3,829.17	9.10	670	5.72	1.58	24.47	92.76
Commercial forest	408.67	0.97	76	5.38	1.27	2.24	90.27
Water	689.21	1.64	33	20.89	1.40	10.49	96.62
Non-forest vegetation cover	643.71	1.53	33	19.51	1.40	127.09	97.90
Urban	380.08	0.90	11	34.55	1.50	17.08	97.95

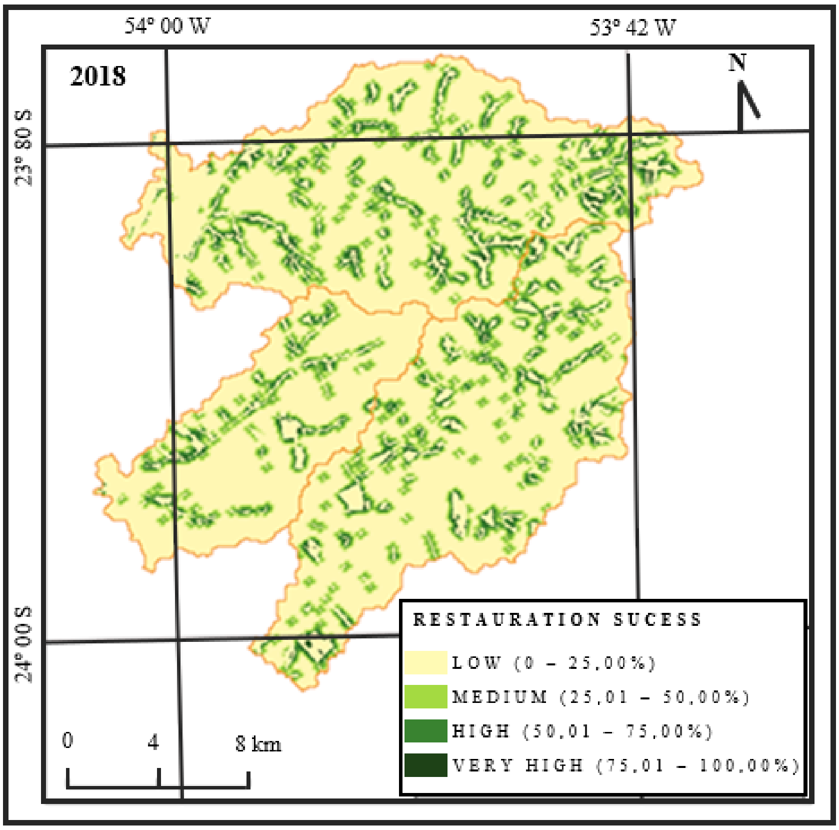
The total class area (CA) of forest cover increased during the analyzed period, with one small decrease in 1996. Moreover, the number of forest fragments (NP) decreased from 573 in 1985 to 540 in 1996 and increased from 551 in 2007 to 670 in 2018. The mean patch area (AREA_MN) of forest cover in all years was considered low, even though it gradually increased from 1996 to 2018. Nevertheless, from 1996 to 2018, the landscape fragmentation decreased. The smallest forest fragment observed was 1 ha in 2018, a value used as a parameter for the successful analysis of forest restoration.

The mean shape index (SHAPE_MN) of forest cover indicated irregularly shaped fragments, with 1.42 in 1985, 1.41 in 1996, 1.56 in 2007, and 1.58 in 2018. The mean proximity index (PROX_MN) of forest cover with other classes has increased since 1996. The connectivity (COHESION) between forest fragments was 90.14 m during the analyzed period. Based on these values, 100 m was used as a parameter in GoFor® for average connectivity to represent the scale of influence between existing fragments and the areas for restoration.

Analysis of forest restoration success

The medium probability class occupied an area of 3,326 ha, while the high probability class occupied 1,795 ha, and the very high probability class occupied 180 ha (Figure 3). Together, medium, high, and very high probability classes represent approximately 12,6 percent of the landscape, covering an area of 5,301 ha. The high and very high success classes are well distributed among the three watersheds, mostly along the watercourses and their surroundings, where there are remaining native forest fragments.

Figure 3. Probability of restoration success in the sub-basins of Rio São João, Ribeirão do Prado, and Rio Iporã, PR, Brazil.



Discussion

The percentages of land use and land cover reflect a transition in the area that was previously used for pasture, being replaced by forest cover and agriculture. Another evidence that supports this change is a greater increase in the NP metric of the forest cover class. This shows that the productive matrix of the studied area has not advanced over forest areas in the last analyzed periods.

The CA (the sum of each class area in ha) and PLAND (the class area percentage in the landscape) metrics indicated an increase in forest cover from 1996 to 2007 mainly along the watercourses (Figure 2). There was also a decrease in pasture areas, suggesting changes in the local rural economy, such as a greater encouragement for planting commercial forests, water, and soil resources conservation practices, as well as compliances with the environmental legislation. According to the Brazilian Forest Code, Law n. 4,771/1965 (Brazil 1965), forest restoration on all riverbanks is mandatory.

Thus, in the early 2000s, the Government of the state of Paraná developed the "*Programa Mata Ciliar*" (Riparian Vegetation Program), which distributed nearly 80 million seedlings of native species for the restoration of the Permanent Preservation Areas (PPAs) from 2003 to 2007 (Renner et al. 2010), among other environmental projects. The increase of forest cover at PPAs shows conformity and effectiveness. However, the encouragement to restore only these areas is not enough to maintain the good quality of the landscape, whereas only considering riverbanks may not allow the gene flow of certain species.

The mean patch shape index (SHAPE_MN) for the forest cover indicated that the fragments have an irregular shape. Nevertheless, these areas are fundamental for the conservation of natural resources and ecological processes, as they form ecological corridors. In the case of other forest fragments that are not PPAs, the edge effect, caused by the irregular shape, must be considered. The edges are influenced by the landscape structure matrix, wherein the more circular the fragment, the larger its central area, which favors ecological processes, such as nutritional exchanges and the establishment of propagating material (Bell et al. 1997). Thus, the shape of the fragment can also impact the ecological interactions between species (Ibáñez and Rodríguez 2020).

The values for the mean proximity index (PROX_MN) increased in the last analyzed years, reinforcing the fragments' potential to favor gene flow between individuals of the same species in surrounding habitats. According to Ibáñez and Rodríguez (2020), the proximity between individuals of the same species influences the success of the ecological restoration.

Cohesion presented a positive but not very expressive result. Calegari et al. (2010) proposed the growth of vegetation corridors in areas dominated by pasture to connect them, thus promoting a better flow of dispersers, pollinators, and propagating material. Another measure for restoration suggested by Borda-Niño et al. (2017) is to protect the largest and better conserved forest fragments through the establishment of protected areas. Therefore, it is also necessary to define areas for restoration between the corridors formed by the PPAs to favor the connection between the forest fragments. Given the complexity of establishing a connection between large areas of continuous fragments, it is suggested, as an alternative, the creation of small islands of habitats that can function as stepping stones between larger fragments with better conditions to promote natural regeneration, as proposed by Forman and Godron (1986). This alternative allows a better displacement of dispersers by reducing the distance for seed distribution (Howe 2014).

Although there is no urban cover in the studied area, the watersheds are highly degraded due to pasture and agriculture, showing few forest fragments – data that was used to calculate the probability of restoration success. Although these classes are more likely to result in harmful processes to the soil, such as erosion, it would not be feasible to determine the entire area as highly restorable, since some places remain very distant from forest fragments.

Only 12.6 percent of the landscape has a high probability of restoration success. However, this does not mean that other places with lower success probably should not be restored as well. As the landscape is composed essentially of agricultural uses, the results show that restoring the vicinity of current sources of native species propagules may be initially more effective. Crouzeilles and Curran (2016) claim that distances shorter than 5 km provide a more direct influence on plant communities by favoring the spread of propagating material, especially in disturbed landscapes.

The use of landscape metrics in a temporal analysis helps GoFor® determine the most suitable locations for intervention of forest restoration activities, increasing the accuracy of these priority areas definition, since landscape metrics allow the understanding of land use dynamics for the restoration process. It is noteworthy that, although ecological parameters can be related to the success of forest restoration, defining priority areas to invest in restoration is laborious and requires different layers of geographic and environmental information. Thus, the main advantage of GoFor® is using little information to generate efficient and fast results.

However, due to the recent creation of this software, some functionalities can still be enhanced to improve the delimitation of restoration areas and generate more successful results. Factors such as restoration method, habitat type, habitat size, and connection between fragments must be considered, as well as socioeconomic parameters of the analyzed area (Crouzeilles and Curran, 2016; Crouzeilles et al. 2019). Furthermore, the opinion and values of people who live inside or near the restoration area must also be addressed, seeking its conciliation with the ecological goals of the restoration process (Stanturf et al. 2014). Furthermore, the success of forest restoration in the three assessed watersheds also depends on the species› potential to establish themselves in the disturbed environment and on the genetic quality of the plants used for restoration.

Even existing forest fragments may need vegetation enrichment to favor their ecological functionality. Rother et al. (2019) found that regenerating plant species diversity can be driven by enrichment plantations with species that are more adapted to environmental disturbances. However, the authors point out that effective restoration in rural landscapes is a challenge, as it requires a balance between ecosystem conservation and agricultural production. Thus, there must be awareness among farmers about the benefits of ecological restoration. Among these benefits are increased soil organic matter, soil and water conservation, pollination, as well as improved air quality and income generation (Robertson et al. 2014).

Due to its pioneering use, it was not possible to deepen, in this research, the discussions about how GoFor® can prioritize regions for forest restoration. However, it is expected that this will contribute to the applicability of the software in different landscape configurations and ecological contexts.

Complying with the Brazilian Forest Code (Brazil 2012) and its legal provisions, such as the state environmental regulation, more programs like the one discussed in this paper are essential as an effort to guarantee ecological restoration in addition to other public policies at the federal, state and local levels towards restoration efforts. These programs can be implemented following the UN Sustainable Development Goals (SDG) guidelines. Among the SDG, the 15th stands out, which aims to protect, restore and promote the sustainable use of terrestrial ecosystems, among other actions related to the sustainable management of forests and soils until 2030 (UN 2022).

In a region where the landscape has been so degraded by human activities, as in the northwest of Paraná, the need for ecological restoration actions is imminent. However, it should be noted that these actions take time to achieve their objectives, so they must be extended over a few decades, with the achievement of one or more ecosystem services gradually (Abhilash 2021). That said, it is expected that the results found in this research can serve as a basis for the elaboration of more in-depth research and, above all, direct restoration actions in the study area.

Conclusions

The landscape of the sub-basins of *Rio São João*, *Ribeirão do Prado*, and *Rio Iporã* is mainly composed of an agricultural matrix. In the last two decades, the natural forest cover increased, but it is still arranged in fragments, which inhibits the establishment of biotic communities.

The success of the forest restoration analysis indicated that most of the landscape has a low probability of obtaining good results from an ecological perspective. Nevertheless, 12.6 percent of the landscape presented a high chance of restoration success, especially along rivers and streams, which can be strategic from a landscape perspective.

The use of landscape metrics as a complement to the success of forest restoration analysis provided more detailed information about the studied area, reducing the uncertainties about the sites to be restored. However, research at other scales and in different contexts of landscape degradation may be necessary.

Acknowledgments

To the "*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*" (Coordination for the Improvement of Higher Education Personnel – CAPES) for granting a doctoral scholarship to the first author. The authors would like to thank the Academic Publishing Advisory Center *(Centro de Assessoria de Publicação Acadêmica,* CAPA – www.capa.ufpr.br) of the Federal University of Paraná (UFPR) for assistance with English language developmental editing.

Participação dos autores: ARNR - conceituação, metodologia, análise dos dados, investigação, curadoria de dados, redação e revisão; DB - supervisão, revisão, administração do projeto; APDC - supervisão e revisão; ACB - supervisão e revisão; FPF - análise dos dados e redação; ECR - análise dos dados e redação; IJCL - análise dos dados e redação; JV - análise dos dados e redação.

Aprovação ética ou licenças de pesquisa: não se aplica.

Disponibilidade dos dados: os dados não estão disponíveis em nenhuma base ou repositório.

Fomento: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) forneceu bolsa a ARNR.

Conflito de Interesses: Os autores declaram não haver conflito de interesses.

References

Abhilash PC. 2021. Restoring the unrestored: strategies for restoring global land during the UN decade on ecosystem restoration (UN-DER). Land 10(2):01-19. htttps://doi.org/10.3390/land10020201

Bell SS, Fonseca MS, Motten LB. 1997. Linking restoration and landscape ecology. Restoration Ecology 1(4):318-323.

Borda-Niño M, Hernandéz-Muciño D, Ceccon E. 2017. Planning restoration in human-modified landscapes: new insights linking different scales. Applied Geography 83:118-129. htttps://doi.org/10.1016/j.apgeog.2017.03.012

Brazil. 1965. Lei nº 4.771, de 15 de setembro de 1965. Código Florestal Brasileiro.

Brazil. 2012. Lei nº 12.651, de 25 de maio de 2012. Código Florestal Brasileiro.

Calegari L, Martins SV, Gleriani JM, Silva E, Busato LC. 2010. Análise da dinâmica de fragmentos florestais no município de Carandaí, MG, para fins de restauração florestal. Árvore 34(5):871-880.

Crouzeilles R, Barros FS, Molin PG, Ferreira MS, Junqueira AB, Chazdon RL, Lindenmeyer DB, Tymus JRC, Strassburg BBN, Brancalion PH. 2019. A new approach to map landscape variation in forest restoration success in tropical and temperate forest biomes. Journal of Applied Ecology 56(12):2675-2686. htttps://doi.org/10.1111/1365-2664.13501

Crouzeilles R, Curran M. 2016. Which landscape size best predicts the influence of forest cover on restoration success? A global meta-analysis on the scale of effect. Journal of Applied Ecology 53(2):440-448. htttps://doi.org/10.1111/1365-2664.12590

Ferrari R, Lachs L, Pygas DR, Humanes A, Sommer B, Figueira WF, Edwards AJ, Bythell JC, Guest JR. 2021. Photogrammetry as a tool to improve ecosystem restoration. Trends in Ecology & Evolution 21:01-09. https://doi.org/10.1016/j.tree.2021.07.004

Ferreira SLS, Oka-Fiori C, Kosciak S. 2012. Análise multitemporal da erosão nas bacias hidrográficas dos rios São João, Iporã e do Prado, Altônia-PR, decorrente da dinâmica agropastoril. Caminhos de Geografia 13(44):15-34.

Forman RTT, Godron M. 1986. Landscape ecology. New York, United States: Wiley, 619 p.

Howe HF. 2014. Diversity storage: implications for tropical conservation and restoration. Global Ecology and Conservation 2:349-358. https://doi.org/10.1016/j.gecco.2014.10.004

Ibáñez I, Rodríguez A. 2020. Understanding neighborhood effects to increase restoration success of woody plant communities. Ecological Applications 30(5):01-11. https://doi.org/10.1002/eap.209

IPARDES - Instituto Paranaense de Desenvolvimento Econômico e Social. 2017. Indicadores de desenvolvimento sustentável por bacias hidrográficas do Estado do Paraná – Curitiba, 141 p.

Koproski LP, Batista AC, Soares RV. 2004. Ocorrências de incêndios florestais no Parque Nacional de Ilha Grande-Brasil. Floresta 34(2):193-197.

Maack R. 2017. Geografia física do Estado do Paraná. Ponta Grossa: Editora UEPG, 526 p.

MAPBIOMAS. 2020. Coleção 3 da série anual de mapas de cobertura e uso de solo do Brasil.

McGarigal K. 2015. Fragstats: Spatial pattern analysis program for categorical maps.

Melo FP, Pinto SR, Brancalion PH, Castro PS, Rodrigues RR, Aronson J, Tabarelli M. 2013. Priority setting for scaling-up tropical forest restoration projects: early lessons from the Atlantic Forest Restoration Pact. Environmental Science & Policy 33:395-404. https://doi.org/10.1016/j.envsci.2013.07.013

Myers N, Mittenmeier RA, Mittenmeier CG, Fonseca GA, Kent J. 2000. Biodiversity hotspots for conservation priorities. Nature 403(6772):853-858.

Oliveira RE, Engel VL. 2017. A restauração florestal na Mata Atlântica: três décadas em revisão. Revista Ciência, Tecnologia & Ambiente 5(1):40-48. https://doi.org/10.4322/2359-6643.05101

Renner RM, Bittencourt SM, Oliveira EB, Radomski MI. 2010. Programa Mata Ciliar no Estado do Paraná: comportamento de espécies florestais plantadas. Colombo: Embrapa Florestas, 38 p.

Robertson GP, Gross KL, Hamilton SK, Landis DA, Schmidt TM, Snapp, SS, Swinton SM. 2014. Farming for ecosystem services: An ecological approach to production agriculture. BioScience 64(5):404-415. https://doi.org/10.1093/biosci/biu037

Rother DC, Liboni AP, Magnago LFS, Chao A, Chazdon RL, Rodrigues RR. 2019. Ecological restoration increases the conservation of taxonomic and functional beta diversity of woody plants in a tropical fragmented landscape. Forest Ecology and Management 451:01-11. https://doi.org/10.1016/j.foreco.2019.117538

Sarmiento JEL, Tymus JRC, Benini RM, Johnson J, Crouzeilles R, Brancalion PHS. 2019. Manual do Usuário GoFor 1.0.x. The Nature Conservancy, 14.

Sousa TR, Costa FRC, Bentos TV, Leal Filho N, Mesquita RCG, Ribeiro IO. 2017. The effect of forest fragmentation on the soil seed bank of Central Amazonia. Forest Ecology and Management 393:105-112. https://doi.org/10.1016/j.foreco.2017.03.020

Stanturf JA, Palik BJ, Dumroese RK. 2014. Contemporary Forest restoration: a review emphasizing function. Forest Ecology and Management 331:292-323. https://doi.org/10.1016/j.foreco.2014.07.029

United Nations (UN). 2019. General Assembly – A/RES/73/284.

United Nations (UN). 2022. Department of Economic and Social Affairs – Sustainable Development. Disponível em: <https://sdgs.un.org/goals/goal15>. Acesso em 12 ago. 2022.

Wrege MS, Fritzsons E. 2015. Dados climáticos dos municípios da região Sul do Brasil. Embrapa Florestas, 441p.