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Articles

Assessment of the recovery stage of degraded areas at a hydroelectric plant in Southern Brazil

Avaliação do estágio de recuperação de áreas degradadas em uma usina hidrelétrica no sul do Brasil

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ABSTRACT

Degraded Area Recovery Plans (DARP) play a fundamental role in environmental management and in the restoration of areas impacted by human activities. Among the projects that most alter land cover and landscape dynamics, hydroelectric plants stand out, generating significant impacts on local ecosystems. The objective of this study was to evaluate the recovery stage of degraded areas of the Machadinho Hydroelectric Power Plant, located in the Uruguay River Basin. Between December 2022 and January 2023, a field assessment was conducted to evaluate the ecological recovery of degraded areas at HPP Machadinho. To assess the stage of recovery was evaluate ecological the follow indicators: Native vegetation cover, Density of native species of the regenerating woody stratum, and Number of native species of the regenerating woody stratum. Additionally, was evaluated the successional stage of secondary forest for secondary vegetation in the Atlantic Forest. A total of 55 tree species and 72 species in the regenerating stratum were record in the study area. The average of native vegetation ground cover was 80.1%. The mean density of regenerating native individuals was 3,788 individuals/ha. The average number of regenerating native species per plot was 9.9. Most of the plots were in an advanced successional stage of regeneration (76.0%). The results show that the recovery process of degraded areas influenced by UHE Machadinho progressed steadily, despite challenges related to the low number of native species in the woody stratum and the presence of exotic species. The combination of natural succession and active management seems to be a viable alternative in the study region. In this sense, we emphasize the importance of establishing evaluation parameters adapted to the successional stage and forest type, which can be used to monitor the progress of ecological restoration.

Keywords: Atlantic Forest; Landscape; Soil recovery; Ecological restoration; Ecological succession

RESUMO

Os Planos de Recuperação de Áreas Degradadas (PRADs) desempenham um papel fundamental na gestão ambiental e na restauração de áreas impactadas por atividades antrópicas. Dentre os projetos que mais alteram a cobertura do solo e a dinâmica da paisagem, destacam-se as usinas hidrelétricas, gerando impactos significativos nos ecossistemas locais. O objetivo deste estudo foi avaliar o estágio de recuperação das áreas degradadas da Usina Hidrelétrica Machadinho, localizada na Bacia do Rio Uruguai. Entre dezembro de 2022 e janeiro de 2023, foi realizada uma avaliação de campo para estimar o grau de recuperação das áreas degradadas na UHE Machadinho. Foram avaliados os seguintes indicadores ecológicos: cobertura do solo com vegetação nativa; densidade de indivíduos nativos regenerantes; e número de espécies nativas regenerantes. Além disso, foi avaliado o estágio sucessional para vegetação secundária na Mata Atlântica. Um total de 55 espécies arbóreas e 72 espécies no estrato de regeneração foi registrado na área de estudo. A média de cobertura do solo por vegetação nativa foi de 80,1%. A densidade média de indivíduos nativos em regeneração foi de 3.788 indivíduos/ha. O número médio de espécies nativas em regeneração por parcela foi de 9,9. A maioria das parcelas encontrava-se em estágio sucessional avançado de regeneração (76,0%). Os resultados mostram que o processo de recuperação das áreas degradadas influenciadas pela UHE Machadinho progrediu de forma constante, apesar dos desafios relacionados ao baixo número de espécies nativas do estrato lenhoso e à presença de espécies exóticas. A combinação de sucessão natural e manejo ativo se mostrou uma alternativa viável na região do estudo. Nesse sentido, enfatizamos a importância de estabelecer parâmetros de avaliação adaptados ao estágio sucessional e ao tipo de floresta, que podem ser usados para monitorar o progresso da restauração ecológica.

Palavras-chave: Mata Atlântica; Paisagem; Recuperação do solo; Restauração ecológica; Sucessão ecológica

1 INTRODUCTION

Restore forests in degraded areas play a critical role in environmental management and in the restoration of areas negatively impacted by anthropogenic activities. Brazilian environmental legislation, particularly Federal Law No 12.651/2012, which regulates the protection of native vegetation, mandates the development and implementation of the Degraded Areas Recovery Project (DARP, or PRAD in Brazilian Portuguese) in cases involving environmental degradation (Brasil, 2012). The DARP must outline specific actions and strategies for the ecological restoration of the areas, including vegetation recovery, erosion control, preservation of water resources, among other components. Therefore, DARP serve as fundamental tools in mitigating environmental impacts and promoting sustainability (Rech et al., 2015).

Among the activities with the most significant impact on land cover is the implementation of Hydroelectric Power Plants (HPP) (Rahman et al., 2022). The construction of HPP involves large-scale infrastructure works that profoundly affect all elements of the landscape. These impacts include the degradation of natural areas due to the establishment of construction sites, leading to the loss of native vegetation and the disruption of natural habitats (Pinto; Oliveira, 2013; Kuriqi et al., 2021). Construction sites and their surroundings are considered highly degraded areas, as the topsoil layers are often removed. After anthropogenic disturbances cease, these areas enter a natural regeneration process that can be slow and ineffective without proper human intervention (Bechara, 2006).

The dynamics of restoration in degraded areas can be influenced by multiple factors, including disturbance history, area size and shape, surrounding land use, and degree of isolation (Bechara, 2006; Bilintoh, 2022). Successful recovery requires management strategies that are adapted to the type and intensity of disturbance, particularly when areas have experienced severe degradation and become dependent on active restoration interventions (Carpanezzi; Nicodemo, 2009; Bahia et al., 2023). Thus, analyzing the recovery process of degraded areas is essential for assessing whether the techniques employed are achieving the restoration objectives defined in the DARP.

Two main strategies for vegetation regeneration are commonly applied: passive natural regeneration and assisted natural regeneration. Passive regeneration allows ecological processes to proceed without significant anthropogenic intervention, typically limited to fencing or establishing firebreaks to exclude disturbances, thereby enabling spontaneous vegetation regrowth. This approach relies on the premise that degraded areas can recover through autogenic successional processes. It is recommended for sites with fertile soils, accessibility to seed-dispersing fauna, and proximity to forest remnants and propagule sources (Rech et al., 2015; Inhamuns et al., 2021).

Assisted natural regeneration, on the other hand, involves targeted actions aimed at stimulating and accelerating natural regeneration processes. These actions may include controlling competing vegetation, excluding herbivores, fertilization, enrichment planting, and increasing vegetation density and nucleation (Allison, 2012; Marcuzzo; Araújo; Gasparin, 2015; Almeida, 2016).

In southern Brazil, along the border between the states of Rio Grande do Sul and Santa Catarina, the Machadinho Hydroelectric Power Plant (HPP Machadinho) is located on the Uruguay River. It began operations in February 2002 and has an installed capacity of approximately 1,140 megawatts (MW), making it one of the largest hydroelectric plants in Brazil in terms of energy production (Consórcio Machadinho, 2021). As part of its environmental commitments, priority areas for restoration were designated within the DARP developed for HPP Machadinho (UFRGS, 2009).

In the states of Rio Grande do Sul and Santa Catarina, there is no specific methodology for monitoring and evaluating environmental recovery in areas where restoration techniques have been applied. Commonly used assessment methods include individual tree counts, vegetation height measurements, and canopy cover evaluation (Glufke, 1999). For the monitoring of restoration areas, protocols from the State of São Paulo, such as Resolution SMA 32/2014 (São Paulo, 2014) and CBRN Ordinance 01/2015 (São Paulo, 2015), are often adopted. These protocols assess forest structure (both horizontal and vertical), soil cover, and the presence of native regenerating species, which serve as indicators of restoration progress.

Understanding the recovery dynamics of degraded areas is relevant from academic, social, and environmental perspectives, especially given the high number of hydroelectric plants built in Brazil, particularly in the Uruguay River basin. While acknowledging the necessity and benefits of such infrastructure for national development and energy generation, it is also important to recognize the significant environmental impacts they cause. In this context, the objective of this study was to evaluate the recovery stage of degraded areas of the Machadinho Hydroelectric Power.

2 MATERIALS AND METHODS

2.1 Study area

The study was conducted in the degraded area recovery zones of the Machadinho Hydroelectric Power Plant (HPP Machadinho), located in the Uruguay River basin between the municipalities of Piratuba (Santa Catarina) and Machadinho (Rio Grande do Sul) (Figure 1). The area was used as construction sites during the plant's building phase. After construction was completed, all temporary structures were removed, and the environmental recovery process was initiated through the planting of native species seedlings, following the guidelines established in the "Ecological Restoration Project for the Areas of the Former Construction Site of the Machadinho Hydroelectric Power Plant" (UFRGS, 2009). The main recovery techniques applied in the area were: soil fertilization and amendment, sowing of herbaceous legumes, planting of native tree seedlings, coverage nuclei with dead organic matter, and control of invasive exotic plant species. These techniques were employed to promote the reestablishment of vegetation cover and the ecological processes of the area.

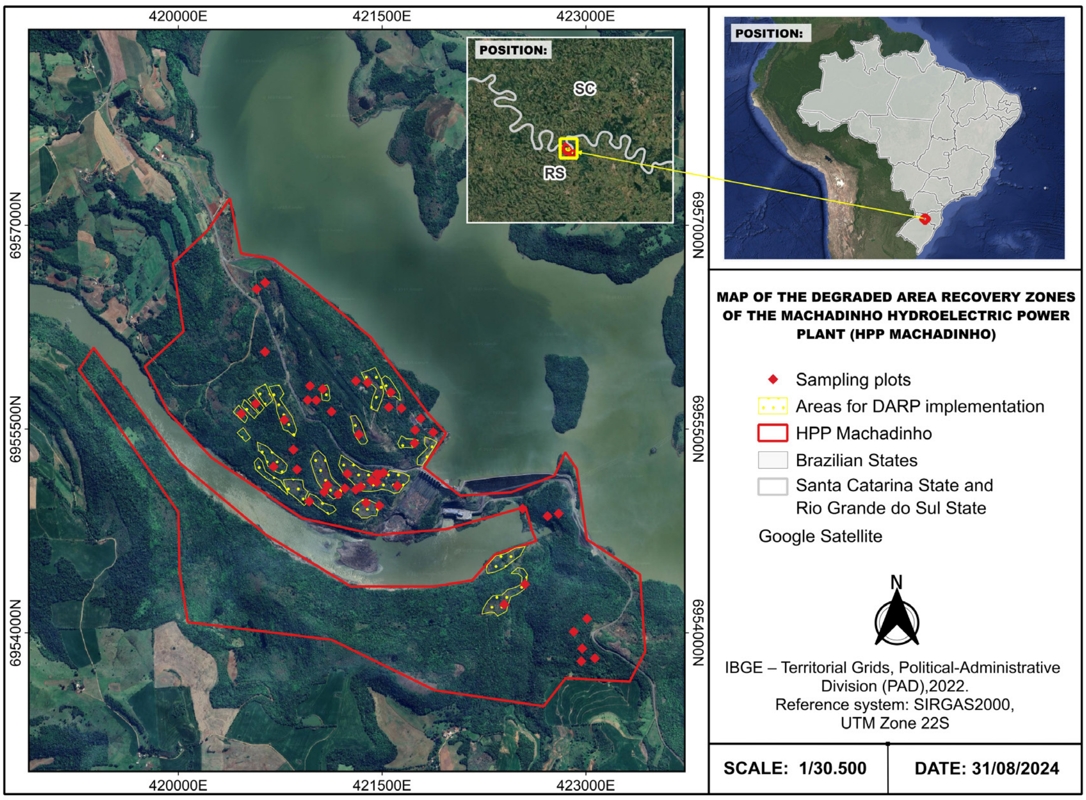
The area lies within the Atlantic Forest biome and includes characteristics of two original forest formations: the Mixed Ombrophilous Forest (Araucaria Forest) and the Deciduous Seasonal Forest (Uruguay Subtropical Forest). The regional climate is humid subtropical, marked by mild temperatures and evenly distributed rainfall throughout the year, with a tendency for heavier rainfall during summer. Average temperatures range from 15°C to 25°C, with relatively cold winters and occasional frosts (Leite; Klein, 1990).

2.2 Data collection

Between December 2022 and January 2023, a field assessment was conducted to evaluate the ecological recovery of degraded areas at HPP Machadinho. Fifty sampling plots were established at the former construction site and its surroundings to assess the recovery stage of the entire area (Figure 1). The number of plots followed the methodology established by Resolution SMA 32/2014 (São Paulo, 2014). Each sampling plot measured 100 m² (25 m x 4 m), defined by a central transect line with 2 m on each side.

Each plot was surveyed once by a team of four researchers. For the measurement of specimens, a measuring tape was used, and height was estimated using a pruning pole. Tree species were identified and classified by family using the (Flora e Funga do Brasil, 2026). Data collected included vertical and horizontal structure parameters: Absolute Dominance (AD), Relative Dominance (RD), Absolute Frequency (AF), Relative Frequency (RF), Importance Value Index (IVI), Coverage Value (CV), Basal Area (BA), Total Volume (VT = BA × 0.4 × height of each individual), Mean Diameter at Breast Height (DBH), and Mean Height (HM) (Sobral et al., 2006).

Figure 1 – Map of sampling plot distribution in the degraded area recovery zone of the Machadinho Hydroelectric Power Plant, located along the Uruguay River, southern Brazil



Source: Authors (2025)

2.3 Data Analyse

To assess the stage of recovery were applied the ecological indicators from Resolution SMA 32/2014 (São Paulo, 2014) and CBRN Ordinance 01/2015 (São Paulo, 2015). 1) Native vegetation cover: percentage of plot area covered by native tree species, measured by the sum of vegetated segments along the 25-meter transect, converted into a percentage of total plot length. 2) Density of native species of the regenerating woody stratum: number of native woody regenerants (shrubs or trees) per hectare, including individuals with height ≥ 50 cm and stem circumference at breast height (CBH) < 15 cm. Counts were scaled to individuals per hectare. 3) Number of native species of the regenerating woody stratum: total number of native woody regenerant species (shrubs or trees) per plot, using the same height and CBH criteria. The native woody regenerants studied across all sampled plots

Thresholds for classifying recovery were established based on these indicators as "Critical," "Minimum," or "Adequate," depending on restoration time (3, 5, 10, and 15 years). A 20-year reference is considered the target for full recovery. For this study, the 10-year benchmark was used, as DARP implementation occurred between 2010 and 2011, and field data were collected in late 2022 an early 2023.

Additionally, the successional stage of secondary forest (Early, Intermediate and Late) was estimated based on CONAMA Resolution No. 33 of December 7, 1994 (Brasil, 1994), which outlines successional stage indicators for secondary vegetation in the Atlantic Forest. Evaluated indicators included: vegetation height, presence of epiphytes and vines, litter layer thickness and quality, biological diversity, understory development, and floristic composition.

The successional stage of regeneration at the time of PRAD implementation was estimated based on the document "Ecological Restoration Project for the Areas of the Former Construction Site of the Machadinho Hydroelectric Power Plant" (UFRGS, 2009). This study describes the history of use, degradation conditions, and the presence of exotic native species in the construction site and its surroundings. It identified 21 distinct areas totaling 43.38 hectares for DARP implementation, with restoration techniques applied between 2010 and 2011 (Figure 1).

3 RESULTS

A total of 55 tree species belonging to 29 families were identified (Table 1) in the degraded area recovery zones of the Machadinho Hydroelectric Power Plant (HPP Machadinho). Among the identified species, four are exotic: *Citrus* sp., *Eryobotrya japonica*, *Hovenia dulcis* and *Psidium guajava* (Zenni; Ziller, 2011; Dechoum et al., 2015, Missio; Longhi, 2019). The most representative family was Fabaceae, with 10 species, followed by Myrtaceae with six species, Lauraceae, Sapindaceae, and Rutaceae, each with three species. A total of 72 species were identified in the regenerating stratum, including 68 native and four exotic species, distributed among 34 families (Table 1). Myrtaceae was the most represented family (10 species), followed by Fabaceae (five species), and Lauraceae and Meliaceae (four species each).

Table 1 – Species and their respective families recorded in the degraded area recovery zones of the Machadinho Hydroelectric Power Plant, located along the Uruguay River on the border between the states of Rio Grande do Sul and Santa Catarina, southern Brazil

Family/specie	Tree species	Regenerating species
Anacardiaceae		
Lithraea brasiliensis Marchand	X	X
Schinus polygamus (Cav.) Cabrera		X
Schinus terebinthifolia Raddi	X	X
Annonacea		
Annona sylvatica A.St.-Hil.	X	
Apocynaceae		
Tabernaemontana catharinensis A.DC.	X	X
Aquifoliaceae		
Ilex paraguariensis A.St.-Hil.	X	X
Araucariaceae		
Araucaria angustifolia (Bertol.) Kuntze	X	X
Arecaceae		
Syagrus romanzoffiana (Cham.) Glassman	X	X
Aspargaceae		
Cordyline spectabilis Kunth & Bouché	X	X
Asterceae		
Baccharis sp.		X

To be continued ...

Table 1 – Continuation

Family/specie	Tree species	Regenerating species
Bignoniaceae		
Handroanthus chrysotrichus (Mart. ex DC.) Mattos	X	X
Jacaranda micrantha Cham.		X
Boraginaceae		
Cordia americana (L.) Gottschling & J.S.Mill.	X	X
Cordia eucalyculata Vell.		X
Cordia trichotoma (Vell.) Arráb. ex Steud.	X	X
Cannabaceae		
Celtis iguanaea (Jacq.) Sarg.		X
Trema micrantha (L.) Blume	X	X
Celastraceae		
Monteverdia ilicifolia (Mart. ex Reissek) Biral		X
Caricaceae		
Carica quercifolia (A.St.-Hil.) Hieron.	X	
Erythroxylaceae		
Erythroxylum deciduum A.St.-Hil.	X	X
Euphorbiaceae		
Alchornea triplinervia (Spreng.) Müll.Arg.		X
Manihot grahamii Hook.		X
Sapium glandulosum (L.) Morong	X	X
Sebastiania commersoniana (Baill.) L.B.Sm. & Downs	X	X
Fabaceae		
Albizia niopoides (Spruce ex Benth.) Burkart	X	
Ateleia glazioveana Baill.	X	
Bauhinia forficata Link	X	X
Enterolobium contortisiliquum (Vell.) Morong	X	
Inga marginata Willd.	X	X
Lonchocarpus campestris Mart. ex Benth.	X	X
Machaerium paraguariense Hassl.	X	
Machaerium stipitatum (DC.) Vogel	X	X
Parapiptadenia rigida (Benth.) Brenan	X	X
Peltophorum dubium (Spreng.) Taub.	X	X
Lamiaceae		
Vitex megapotamica (Spreng.) Moldenke		X
Lauraceae		
Nectandra lanceolata Nees	X	X
Nectandra megapotamica (Spreng.) Mez	X	X
Ocotea indecora (Schott) Mez		X
Ocotea puberula (Rich.) Nees	X	X

To be continued ...

Table 1 – Continuation

Family/specie	Tree species	Regenerating species
Loganiaceae		
Strychnos brasiliensis (Spreng.) Mart.		X
Malvaceae		
Ceiba speciosa (A.St.-Hil.) Ravenna	X	
Heliocarpus americanus L.		X
Luehea divaricata Mart. & Zucc.	X	X
Melastomataceae		
Miconia sp.		X
Meliaceae		
Cabralea canjerana (Vell.) Mart.	X	X
Cedrela fissilis Vell.	X	
Guarea macrophylla Vahl		X
Trichilia clausenii C.DC.		X
Trichilia elegans A.Juss.		X
Mimosaceae		
Mimosa bimucronata (DC.) Kuntze	X	X
Moraceae		
Maclura tinctoria (L.) D.Don ex Steud.	X	
Myrtaceae		
Campomanesia guazumifolia (Cambess.) O.Berg	X	X
Campomanesia xanthocarpa (Mart.) O.Berg	X	X
Eugenia involucrata DC.	X	X
Eugenia pyriformis Cambess.		X
Eugenia uniflora L.	X	X
Myrcia sp.		X
Myrcianthes pungens (O.Berg) D.Legrand		X
Plinia peruviana (Poir.) Govaerts		X
Psidium cattleyanum Sabine	X	X
Psidium guajava L.	X	X
Phyllantaceae		
Phyllanthus sellowianus (Klotzsch) Müll.Arg.		X
Piperaceae		
Piper aduncum L.	X	X
Primulaceae		
Myrsine coriacea (Sw.) R.Br. ex Roem. & Schult.	X	X
Myrsine umbellata Mart.	X	X
Rhamnaceae		
Hovenia dulcis Thunb. *	X	X

To be continued ...

Table 1 – Conclusion

Family/specie	Tree species	Regenerating species
Rosaceae		
Eriobotrya japonica (Thunb.) Lindl. *	X	X
Prunus myrtifolia (L.) Urb.	X	X
Rubus rosifolius Sm. *		X
Rutaceae		
Citrus sp*	X	
Citrus sp. *	X	X
Helietta apiculata Benth.		X
Pilocarpus pennatifolius Lem.	X	X
Salicaceae		
Casearia sylvestris Sw.	X	X
Sapindaceae		
Allophylus edulis (A.St.-Hil., Cambess. & A.Juss.) Radlk.	X	X
Cupania vernalis Cambess.	X	X
Matayba elaeagnoides Radlk.	X	X
Sapotaceae		
Chrysophyllum gonocarpum (Mart. & Eichler ex Miq.) Engl.		X
Chrysophyllum marginatum (Hook. & Arn.) Radlk.		X
Solanaceae		
Cestrum intermedium Sendtn.		X
Solanum mauritianum Scop.	X	
Solanum sp.		X
Winteraceae		
Drimys brasiliensis Miers		X

Source: Authors (2025)

In where: (*) exotic species.

A total of 530 individual trees were recorded, corresponding to an estimated density of 1,064 individuals per hectare. The species with the highest density were *Schinus terebinthifolia* with 136 individuals/ha, followed by *Luehea divaricata* with 124 individuals/ha, and *Parapiptadenia rigida* with 120 individuals/ha. Also noteworthy were *Lonchocarpus campestris* with 96 individuals/ha, *Psidium cattleianum* with 74 individuals/ha, and *Ocotea puberula* with 68 individuals/ha. The species with the greatest dominance was *Parapiptadenia rigi*da, with 3.75 m²/ha of basal area. It was followed by *Luehea divaricata* (3.72 m²/ha), *Psidium cattleianum* (1.89 m²/ha), *Schinus terebinthifolia s* (1.72 m²/ha), and *Enterolobium contortisiliquum* (1.33 m²/ha) (Table 2).

The Importance Value Index (IVI), derived from the combined values of relative density, dominance, and frequency, indicated that *Luehea divaricata* is the most ecologically significant species in the sampled community, with an IVI of 38.22%. It was followed by *Parapiptadenia rigida* (34.89%), *Schinus terebinthifolia* (29.93%), *Psidium cattleianum* (21.52%), *Lonchocarpus campestris* (19.16%), and *Ocotea puberula* (18.07%). Together, these six species account for more than half of the total IVI for all species and are therefore considered the dominant components of the study area (Table 2).

The main species in the upper canopy according to IVI were *Luehea divaricata*, *Araucaria angustifolia*, *Nectandra megapotamica*, *Ocotea puberula*, *Parapiptadenia rigida*, *Cupania vernalis*, *Sapium glandulosum*, *Syagrus romanzoffiana*, and *Ceiba speciosa*. In the mid-story stratum, the most representative species were *Inga marginata*, *Psidium cattleyanum*, *Enterolobium contortisiliquum*, *Machaerium stipitatum*, *Myrsine coriacea*, *Cordia americana*, *Lonchocarpus campestris*, *Bauhinia forficata*, *Allophylus edulis*, and *Annona sylvatica*, among others. The lower stratum included species such as *Casearia sylvestris*, *Campomanesia guazumifolia*, *Lithraea brasiliensis*, *Schinus terebinthifolia*, *Eugenia uniflora*, and *Solanum mauritianum* (Table 3).

Table 2 – Horizontal structure in the degraded area recovery zones of the Machadinho Hydroelectric Power Plant, located along the Uruguay River on the border between the states of Rio Grande do Sul and Santa Catarina, southern Brazil

Species	**IVI (%)**	**AD (ind/ha)**	**RD (%)**	**AF (%)**	**RF (%)**	**VC (%)**
Psidium cattleyanum Sabine	21,52	74	6,80	160	6,22	15,30
Lonchocarpus campestris Mart. ex Benth.	19,16	96	8,82	130	5,05	14,10
Ocotea puberula (Rich.) Nees	18,07	68	6,25	180	7,00	11,07
Sapium glandulosum (L.) Morong	15,14	46	4,23	160	6,22	8,92
Lithraea brasiliensis Marchand	5,50	22	2,02	70	2,72	2,78
Machaerium stipitatum (DC.) Vogel	4,05	12	1,10	50	1,94	2,11
Myrsine umbellata Mart.	3,44	14	1,29	40	1,56	1,89

To be continued ...

Table 2 – Continuation

Species	IVI (%)	AD (ind/ha)	RD (%)	AF (%)	RF (%)	VC (%)
Nectandra lanceolata Nees	3,28	8	0,74	40	1,56	1,72
Erythroxylum deciduum A.St.-Hil.	3,21	12	1,10	50	1,94	1,27
Casearia sylvestris Sw.	3,08	14	1,29	10	0,39	2,69
Peltophorum dubium (Spreng.) Taub.	2,57	8	0,74	40	1,56	1,02
Zanthoxylum rhoifolium Lam.	2,53	6	0,55	30	1,17	1,36
Ateleia glazioveana Baill.	2,39	10	0,92	4	0,16	2,24
Helietta apiculata Benth.	2,24	12	1,10	20	0,78	1,46
Cupania vernalis Cambess.	2,20	6	0,55	30	1,17	1,04
Cordia americana (L.) Gottschling & J.S.Mill.	2,01	6	0,55	30	1,17	0,84
Myrsine coriacea (Sw.) R.Br. ex Roem. & Schult.	1,35	4	0,37	20	0,78	0,58
Machaerium paraguariense Hassl.	1,26	4	0,37	20	0,78	0,48
Eugenia involucrata DC.	1,25	4	0,37	20	0,78	0,47
Cordyline spectabilis Kunth & Bouché	1,21	4	0,37	20	0,78	0,43
Piper aduncum L.	1,18	4	0,37	20	0,78	0,40
Bauhinia forficata Link	1,16	8	0,74	8	0,31	0,85
Rubus rosifolius Sm.	1,11	4	0,37	10	0,39	0,72
Mimosa bimucronata (DC.) Kuntze	1,00	6	0,55	10	0,39	0,61
Carica quercifolia (A.St.-Hil.) Hieron.	0,32	2	0,18	2	0,08	0,24
Allophylus edulis (A.St.-Hil., Cambess. & A.Juss.) Radlk.	0,29	2	0,18	2	0,08	0,21
Citrus sp.	0,28	2	0,18	2	0,08	0,20
Enterolobium contortisiliquum (Vell.) Morong	7,89	8	0,74	30	1,17	6,72
Hovenia dulcis Thunb.	6,87	30	2,76	70	2,72	4,15
Prunus myrtifolia (L.) Urb.	5,85	22	2,02	70	2,72	3,13
Solanum mauritianum Scop.	1,83	6	0,55	30	1,17	0,66
Syagrus romanzoffiana (Cham.) Glassman	7,82	18	1,65	90	3,50	4,32
Araucaria angustifolia (Bertol.) Kuntze	4,76	18	1,65	10	0,39	4,37
Ceiba speciosa (A.St.-Hil.) Ravenna	4,76	14	1,29	8	0,31	4,45
Ilex paraguariensis A.St.-Hil.	2,76	10	0,92	40	1,56	1,20
Nectandra megapotamica (Spreng.) Mez	4,70	18	1,65	50	1,94	2,75
Psidium guajava L.	2,70	8	0,74	40	1,56	1,14
Inga marginata Willd.	1,69	6	0,55	20	0,78	0,91
Cedrela fissilis Vell.	2,62	12	1,10	12	0,47	2,16
Cordia trichotoma (Vell.) Arráb. ex Steud.	4,61	10	0,92	20	0,78	3,83
Albizia niopoides (Spruce ex Benth.) Burkart	0,79	4	0,37	4	0,16	0,63
Annona sylvatica A.St.-Hil.	0,71	4	0,37	4	0,16	0,55
Cabralea canjerana (Vell.) Mart.	0,89	6	0,55	6	0,23	0,66
Campomanesia guazumifolia (Cambess.) O.Berg	0,92	8	0,74	2	0,08	0,84
Campomanesia xanthocarpa (Mart.) O.Berg	0,61	4	0,37	4	0,16	0,46
Eugenia uniflora L.	0,61	2	0,18	10	0,39	0,23

To be continued ...

Table 2 – Continuation

Species	IVI (%)	AD (ind/ha)	RD (%)	AF (%)	RF (%)	VC (%)
Handroanthus pulcherrimus (Sandwith) S.O.Grose	0,77	2	0,18	10	0,39	0,38
Luehea divaricata Mart. & Zucc.	38,22	124	11,40	260	10,11	28,11
Maclura tinctoria (L.) D.Don ex Steud.	0,68	2	0,18	10	0,39	0,29
Matayba elaeagnoides Radlk.	0,87	2	0,18	10	0,39	0,48
Parapiptadenia rigida (Benth.) Brenan	34,89	120	11,03	180	7,00	27,89
Schinus terebinthifolia Raddi	29,93	136	12,50	250	9,72	20,21
Sebastiania commersoniana (Baill.) L.B.Sm. & Downs	0,99	6	0,55	10	0,39	0,60
Tabernaemontana catharinensis A.DC.	0,60	2	0,18	10	0,39	0,21
Trema micrantha (L.) Blume	0,60	2	0,18	10	0,39	0,21
Total	300	1064	100	2452	100	200

Source: Authors (2025)

In where: Absolute Dominance (AD), Relative Dominance (RD), Absolute Frequency (AF), Relative Frequency (RF), Importance Value Index (IVI), Coverage Value (CV).

Table 3 – Vertical structure in the degraded area recovery zones of the Machadinho Hydroelectric Power Plant, located along the Uruguay River on the border between the states of Rio Grande do Sul and Santa Catarina, southern Brazil

Specie	nºTree	BA (m^2)	VT (m^3)	DBH (m)	HM (m)
Schinus terebinthifolia Raddi	68	0,8575	1,7595	0,1081	4,5
Luehea divaricata Mart. & Zucc.	62	1,8582	6,4993	0,1547	6,8
Parapiptadenia rigida (Benth.) Brenan	60	1,8743	6,0698	0,1663	6,3
Lonchocarpus campestris Mart. ex Benth.	48	0,5868	1,3505	0,1133	5,8
Psidium cattleyanum Sabine	37	0,9444	2,3491	0,1557	5,3
Ocotea puberula (Rich.) Nees	34	0,5359	1,4761	0,1313	6,3
Sapium glandulosum (L.) Morong	23	0,5216	1,5712	0,1391	5,9
Hovenia dulcis Thunb.	15	0,1549	0,397	0,107	5,9
Lithraea brasiliensis Marchand	11	0,084	0,1528	0,0967	4,5
Prunus myrtifolia (L.) Urb.	11	0,1234	0,4417	0,1143	8,2
Araucaria angustifolia (Bertol.) Kuntze	9	0,3021	1,3168	0,185	8,2
Nectandra megapotamica (Spreng.) Mez	9	0,1221	0,5109	0,1093	8,3
Syagrus romanzoffiana (Cham.) Glassman	9	0,2962	1,1385	0,1846	7,5
Casearia sylvestris Sw.	7	0,1558	0,5426	0,1532	7,9
Ceiba speciosa (A.St.-Hil.) Ravenna	7	0,3518	1,3074	0,2192	7,1
Myrsine umbellata Mart.	7	0,0668	0,1699	0,1023	5,9

To be continued ...

Table 3 – Continuation

Specie	nºTree	BA (m²)	VT (m³)	DBH (m)	HM (m)
Cedrela fissilis Vell.	6	0,1173	0,3008	0,1369	5,4
Erythroxylum deciduum A.St.-Hil.	6	0,0183	0,0267	0,0594	4,4
Helietta apiculata Benth.	6	0,0402	0,0893	0,0817	5,5
Machaerium stipitatum (DC.) Vogel	6	0,112	0,441	0,1507	9,4
Ateleia glazioveana Baill.	5	0,1464	0,3005	0,1859	4,7
Cordia trichotoma (Vell.) Arráb. ex Steud.	5	0,3237	1,4554	0,1783	7,4
Ilex paraguariensis A.St.-Hil.	5	0,0312	0,0586	0,0859	4,9
Bauhinia forficata Link	4	0,013	0,0269	0,0629	4,6
Campomanesia guazumifolia (Cambess.) O.Berg	4	0,0119	0,0231	0,0605	4,6
Enterolobium contortisiliquum (Vell.) Morong	4	0,6657	2,3894	0,4186	8,6
Nectandra lanceolata Nees	4	0,11	0,4853	0,1456	10
Peltophorum dubium (Spreng.) Taub.	4	0,0316	0,0748	0,0955	5,7
Psidium guajava L.	4	0,0454	0,0813	0,1035	3,5
Cabralea canjerana (Vell.) Mart.	3	0,012	0,0278	0,069	4,7
Cordia americana (L.) Gottschling & J.S.Mill.	3	0,0325	0,0841	0,1167	6,5
Cupania vernalis Cambess.	3	0,0538	0,1838	0,1475	8,3
Inga marginata Willd.	3	0,0403	0,1072	0,1273	5,8
Mimosa bimucronata (DC.) Kuntze	3	0,0061	0,0069	0,0509	2,8
Gymnanthes klotzschiana Müll.Arg.	3	0,0059	0,008	0,0499	3,5
Solanum mauritianum Scop.	3	0,012	0,0199	0,07	4,5
Zanthoxylum rhoifolium Lam.	3	0,09	0,2385	0,156	7
Albizia niopoides (Spruce ex Benth.) Burkart	2	0,0297	0,0701	0,1369	6
Annona sylvatica A.St.-Hil.	2	0,0203	0,0534	0,113	6,5
Cordyline spectabilis Kunth & Bouché	2	0,0067	0,0104	0,0653	4
Eugenia involucrata DC.	2	0,0112	0,0207	0,0844	4,5
Machaerium paraguariense Hassl.	2	0,013	0,0296	0,0907	5,5
Myrsine coriacea (Sw.) R.Br. exRoem. & Schult.	2	0,0233	0,0691	0,1194	6,8
Piper aduncum L.	2	0,0041	0,0061	0,0509	3,8
Rubus rosifolius Sm.	2	0,0392	0,0498	0,156	3,3
Allophylus edulis (A.St.-Hil., Cambess. & A.Juss.) Radlk.	1	0,0032	0,0102	0,0637	8
Campomanesia xanthocarpa (Mart.) O.Berg	1	0,0032	0,0057	0,0637	4,5
Carica quercifolia (A.St.-Hil.) Hieron.	1	0,0067	0,0094	0,0923	3,5
Citrus sp.	1	0,0023	0,0032	0,0541	3,5
Eugenia uniflora L.	1	0,0046	0,0055	0,0764	3
Handroanthus pulcherrimus (Sandwith) Mattos	1	0,0215	0,0689	0,1655	8
Maclura tinctoria (L.) D.Don ex Steud.	1	0,0115	0,046	0,121	10
Matayba elaeagnoides Radlk.	1	0,0326	0,1304	0,2037	10

To be continued ...

Table 3 – Conclusion

Specie	nºTree	BA (m²)	VT (m³)	DBH (m)	HM (m)
Tabernaemontana catharinensis A.DC.	1	0,0026	0,0041	0,0573	4
Trema micrantha (L.) Blume	1	0,0032	0,0095	0,0637	7,5
TOTAL	530	10,994	34,0845	6,5708	328,6

Source: Authors (2025)

In where: nº Tree (number of trees per sampling plot), Basal Area (BA), Total Volume (VT = BA × 0.4 × height of each individual), Diameter at Breast Height (DBH), and Mean Height (HM).

The average of native vegetation ground cover was 80.1%. Of the 50 sampling plots, six (12.0%) were classified as Critical, nine (18.0%) as Minimum, and 32 (64.0%) as Adequate. The mean density of regenerating native individuals was 3,788 individuals/ha. None of the plots were classified as Critical; nine plots (18.0%) were categorized as Minimum, and 41 plots (82.0%) as Adequate (Table 4).

The average number of regenerating native species per plot was 9.9. Of the 50 plots, 26 (52.0%) were classified as Critical, 24 (48.0%) as Minimum, and none as Adequate (Table 4). Most of the plots were in an advanced successional stage of regeneration (38 plots; 76.0%), followed by nine plots (18.0%) in intermediate stage, and three plots (6.0%) in initial stage (Table 4). At the time of the DARP implementation, all 21 areas were in the initial stage of natural regeneration.

Chart 1 – Ecological indicators of stages of recovery according to Resolution SMA 32/2014 (São Paulo, 2014) and CBRN Ordinance 01/2015 (São Paulo, 2015); and successional stage of secondary forest according CONAMA Resolution 33/1994 (Brasil, 1994)

Sampling plots	Native vegetation cover (%)	Density of native species (ind/ha)	Number of native species per plot	Successional stage
P1	34	1700	7	Intermediate
P2	64	4900	10	Early
P3	84	6300	13	Intermediate
P4	100	6500	12	Intermediate
P5	92	5700	20	Early
P6	86	10800	16	Intermediate

To be continued ...

Chart 1 – Continuation

Sampling plots	Native vegetation cover (%)	Density of native species (ind/ha)	Number of native species per plot	Successional stage
P7	82	2700	11	Intermediate
P8	36	2200	3	Intermediate
P9	78	1100	6	Intermediate
P10	62	1400	6	Intermediate
P11	100	4600	15	Intermediate
P12	88	3700	9	Intermediate
P13	80	1100	3	Late
P14	100	2700	3	Intermediate
P15	100	1600	8	Late
P16	100	4700	15	Late
P17	92	3000	9	Intermediate
P18	58	2500	9	Intermediate
P19	100	3300	15	Intermediate
P20	100	7900	14	Intermediate
P21	100	5800	16	Intermediate
P22	100	7300	15	Intermediate
P23	68	5400	12	Intermediate
P24	100	2500	8	Early
P25	100	6600	19	Late
P26	100	3400	13	Intermediate
P27	100	2400	6	Intermediate
P28	100	3000	8	Intermediate
P29	100	3800	11	Intermediate
P30	100	2300	11	Late
P31	66	1900	9	Intermediate
P32	24	2200	13	Intermediate
P33	32	2500	7	Late
P34	24	1600	3	Intermediate
P35	100	3600	11	Intermediate
P36	84	3300	8	Intermediate
P37	88	6200	15	Late
P38	100	3700	10	Intermediate
P39	28	1100	2	Late
P40	84	1300	8	Intermediate
P41	64	4200	13	Intermediate
P42	100	7000	14	Late
P43	100	5200	13	Intermediate
P44	60	3400	9	Intermediate
P45	100	2500	6	Intermediate

To be continued ...

Chart 1 – Conclusion

Sampling plots	Native vegetation cover (%)	Density of native species (ind/ha)	Number of native species per plot	Successional stage
P46	100	3900	10	Intermediate
P47	68	2700	8	Intermediate
P48	60	3700	8	Intermediate
P49	40	4800	4	Intermediate
P50	82	3700	5	Intermediate

Source: Authors (2025)

In where: Machadinho Hydroelectric Power Plant, located along the Uruguay River on the border between the states of Rio Grande do Sul and Santa Catarina, southern Brazil. Reference benchmark values for 10 years according to São Paulo State Resolution 32/2014: Red (Critical), Blue (Minimum), Green (Adequate).

3 DISCUSSIONS

The floristic composition identified in the study area reflects ongoing ecological succession patterns, with families such as Fabaceae, Myrtaceae, and Lauraceae exhibiting higher species richness. These families are frequently observed in natural regeneration processes due to their effective dispersal strategies and tolerance to adverse environmental conditions (Chazdon, 2008). The predominance of species from the Fabaceae family (10 species) aligns with findings from other studies that highlight the importance of this family in secondary forests and regenerating environments. Fabaceae exhibit several traits that favor their establishment in recovering areas (Coletta, 2010; Pereira; Rodrigues, 2012; Lopes, 2020).

Prior to the implementation of the PRAD, the areas exhibited low vegetation cover as a result of the construction activities related to the hydroelectric plant. The existing vegetation was predominantly composed of pioneer and opportunistic species, notably *Andropogon bicornis, Schinus terebinthifolia*, and *Baccharis* spp. These species established themselves through natural regeneration, from seed dispersal originating from remaining forest fragments located in the surrounding area. The proximity of these forest remnants facilitated the arrival of propagules through various dispersal agents, such as wind, birds, and mammals, contributing to the initiation of the ecological succession process prior to the execution of the recovery actions prescribed in the DARP.

The presence of exotic species such as *Hovenia dulcis*, *Psidium guajava*, *Rubus rosifolius* and *Citrus* sp., can hinder the recovery process of degraded areas. Exotic species may compete with native flora for resources, altering community composition and delaying restoration processes (Simberloff et al., 2013; Richardson; Pysek, 2007). These four species exhibit varying invasive potentials. *Hovenia dulcis* demonstrates a high capacity for invasion in subtropical forests, particularly in shaded environments (Zenni; Ziller, 2011; Dechoum et al., 2015). *Psidium guajava* is considered a serious invasive species, forming dense thickets that outcompete native vegetation (Missio; Longhi, 2019). *Rubus rosifolius* invades forest understories, forming thorny clumps that suppress native regeneration (Ziller; Dechoum, 2013). In contrast, *Citrus* sp. may act as a naturalized species, although its invasive status requires site-specific assessment (Missio; Longhi, 2019). Active management strategies, such as invasive species removal and floristic enrichment, may be necessary to enhance restoration outcomes (Holl; Brancalion, 2020).

The phytosociological structure revealed a density of 1,064 individuals per hectare, which falls within the expected range for secondary forests and fragments undergoing ecological succession (Silva et al., 2010). This density suggests a strong natural regeneration capacity in the area, consistent with intermediate successional stages. The most abundant species, *Schinus terebinthifolia*, *Luehea divaricata*, and *Parapiptadenia rigida*, are commonly found in forest formations in southern Brazil and play essential roles in forest structure and dynamics, acting either as pioneer species or as facilitators of succession (Silva et al., 2010). For instance, *Schinus terebinthifolia* is a widely distributed species recognized for its rapid colonization capabilities, serving as an indicator of regenerating environments (Carvalho; Nakajima, 2009).

High dominance values for species such as *Parapiptadenia rigida*, *Luehea divaricata*, and *Psidium cattleyanum* influence environmental factors such as light availability, resource competition, and microhabitat formation (de Souza *et al*, 2025). *Parapiptadenia rigida* is typically associated with well-drained soils and recovering areas, characterizing more advanced successional stages. The high importance value index (IVI) of *Luehea divaricata*, followed by *Parapiptadenia rigida* and *Schinus terebinthifolia*, corroborates studies that highlight *Luehea divaricata* as a widely distributed and ecologically significant species in southern Brazilian forests (Carvalho; Nakajima, 2009; Oliveira et al, 2025).

The horizontal and vertical structure indicates that species with the highest IVI play a predominant role in local vegetation dynamics, contributing to ecosystem stability and continuity (Silva et al., 2010). These results also suggest an ongoing successional process, with the presence of both pioneer and late secondary species, indicating positive progress in ecosystem recovery. The vertical stratification observed in the study area is characteristic of forest ecosystems at various regeneration stages. The presence of species such as *Luehea divaricata*, *Araucaria angustifolia*, and *Nectandra megapotamica* in the canopy layer highlights their importance in forest structure, given their contribution to floristic composition and resource availability for associated fauna.

The intermediate stratum, composed of species like *Inga marginata*, *Psidium cattleyanum*, and *Machaerium stipitatum*, reflects a transitional layer between the established canopy and the developing understory. These species are frequently found in secondary forests (Silva; Cordeiro; Arzolla, 2022). Moreover, lower stratum species such as *Schinus terebinthifolia* and *Eugenia uniflora* play a fundamental role in reestablishing forest cover by maintaining biodiversity and providing substrate for the growth of taller species.

The percentage of native vegetation cover indicates that natural vegetation recovery is progressing, with the area showing a positive trend in soil cover restoration.

The mean native vegetation cover exceeded 80%, with 64% of the sampling plots classified as adequately restored. These findings suggest a progressive environmental recovery process. Ecological restoration of these areas requires effective strategies, with native vegetation cover playing a key role (Rodrigues; Gandolfi, 2004). Native plants significantly improve the physical, chemical, and biological properties of the soil. Their root systems stabilize the soil, reducing water and wind erosion (Lepsch, 2010). Additionally, organic matter from native vegetation contributes to soil fertility and enhances water and nutrient retention.

Another critical aspect of native vegetation cover is its role in promoting biodiversity. Native vegetation offers habitat and food resources for diverse fauna, facilitating the recovery of natural ecosystems (Souza; Batista, 2004). Flora–fauna interactions are essential for key ecological processes, such as seed dispersal and pollination, which accelerate the regeneration of degraded areas. The implementation of revegetation programs using native species also yields socioeconomic benefits. In addition to improving environmental quality, restoration initiatives can foster sustainable development through activities such as ecotourism and the sustainable use of natural resources (Ferreira et al., 2018), provided they are well planned and executed in designated areas. Therefore, native vegetation cover is a decisive factor in the recovery of degraded lands, positively impacting soil stability, fertility, biodiversity, and long-term sustainability.

The density of native species of the regenerating woody stratum and the percentage of adequately restored areas (reaching 80%) indicate progress in forest structure recovery. In early recovery stages, pioneer species colonization is often slow due to adverse conditions such as limited propagule availability and low soil moisture retention (Chazdon, 2014; Cruz et al, 2024). Over time, improvements in microenvironmental conditions—such as increased vegetation cover and the development of a soil seed bank—facilitate the establishment and growth of new species, including both early and late secondary species (Guariguata; Ostertag, 2001).

These results may be linked to the ecological resilience of the area and environmental conditions that favor forest species dispersal and establishment (Souza; Batista, 2004).

Plots classified as critical or minimal in terms of density of native species of the regenerating woody stratum may be experiencing local limiting factors, such as interspecific competition, herbivory pressure, or anthropogenic disturbances. Additionally, seed limitation or unfavorable edaphic conditions may act as barriers to seedling recruitment and growth.

The number of native species of the regenerating woody stratum is consistent with studies reporting progressive vegetation recovery in degraded areas over time (Chazdon, 2014). However, when evaluating species richness per plot, none of the areas met the adequacy level expected after 10 years, with 26 plots classified as critical. Despite observed improvements in vegetation structure and cover, the lack of plots with adequate species richness for 10 years highlights ongoing challenges in achieving full functional recovery.

Soil quality is a key determinant of vegetation development, and degraded or nutrient-poor soils limit the number of species that can successfully establish. Soil compaction, low nutrient availability, and organic matter loss reduce water retention capacity and microbial activity, thereby impairing seedling germination and growth. Furthermore, soil contamination or altered pH levels can create unfavorable conditions for ecological succession, often favoring invasive over native species (Carvalho; Santos; Pe reira, 2023). Thus, restoring soil quality through organic matter inputs and microbial recovery is essential for promoting natural regeneration and increasing species richness (Almeida *et al*., 2024). Beyond ecological factors, it is important to consider that the regulatory standards used for comparison are based on Atlantic Forest parameters from southeastern Brazil. For Ombrophilous and Mixed Forests in southern Brazil, expectations regarding diversity may differ.

The advancement of successional stage of secondary forest, with 94% of plots classified as being in intermediate (76%) or advanced (18%) stages, is consistent with successional transition models, where the establishment of secondary and late-successional species contributes to ecosystem structural complexity and stabilization (Guariguata; Ostertag, 2001).

The recovery rate varies by biome, initial disturbance intensity, and the restoration strategies employed (Ferreira et al., 2018). Successful regeneration depends on proper planning and continuous monitoring (Carvalho; Santos; Pereira, 2023). Well-designed and implemented DARP can lead to high regeneration rates, bringing degraded lands closer to the original native vegetation over time. Vegetation regeneration in areas impacted by hydroelectric projects appears to follow similar patterns observed in other degraded landscapes with altered soil cover. However, questions remain regarding their ability to return to a functionally equivalent state compared to the original ecosystem.

4 CONCLUSIONS

The results indicate that the DARP implemented in the HPP Machadinho recovery areas has produced satisfactory outcomes, with most ecological indicators meeting the 10-year benchmarks set by São Paulo State Ordinance SMA 32/2014. The recovery process progressed steadily, despite challenges related to the low number of native species in the woody stratum and the presence of exotic species. The combination of natural succession and active management seems to be a viable alternative in the study region. In this sense, we emphasize the importance of establishing evaluation parameters adapted to the successional stage and forest type, which can be used to monitor the progress of ecological restoration.

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