REVISTA FLORESTA
Engenharia Florestal
ISSN 1982-4688
Edição 56
Universidade Federal do Paraná
Setor de Ciências Agrárias

RIVER SLOPE RECOVERY USING NATURAL ENGINEERING TECHNIQUE

Rodrigo Fischer Meinert[1*], Rosemeri Carvalho Marenzi[2]

[1*]Coastal Conservation and Management Laboratory, Universidade do Vale do Itajaí, Itajaí, Santa Catarina, Brazil – rodrigo.meinert@gmail.com
[2]Coastal Conservation and Management Laboratory, Universidade do Vale do Itajaí, Itajaí, Santa Catarina, Brazil – merimarenzi@univali.br

Received for publication: 29/04/2025 – Accepted for publication: 03/03/2026

Resumo

Recuperação de Talude Fluvial Utilizando Técnica de Engenharia Natural. A erosão causada por *Bambusa tuldoides* Munro e a ausência de vegetação nativa nas margens do Rio Camboriú, no Parque Natural Municipal Raimundo Gonçalez Malta, motivou a aplicação de técnicas de Engenharia Natural para sua contenção. A intervenção consistiu no ajuste do talude (50°) e instalação de quatro Grades Vivas de bambu (4 m² cada), preenchidas com solo argiloso, para o plantio de *Hibiscus tiliaceus* L. (estaquia viva) e *Acrostichum aureum* L. (mudas). Uma cerca permeável de bambu foi construída para reduzir o impacto das ondas de embarcações. Para avaliação, uma Área Controle semelhante, sem intervenção, foi monitorada. Observou-se acúmulo de solo na área tratada e agravamento da erosão na Área Controle. A taxa de enraizamento de *H. tiliaceus* que foram mantidos em casa de vegetação foi de 42,5%; e em campo, a sobrevivência foi de 9% (estacas enraizadas) e 8% (estacas não enraizadas). *A. aureum* apresentou 20% de sobrevivência. A cobertura vegetal média nas Grades Vivas foi de 20%, sem diferenças significativas entre topo e base (t=0,13793; p=0,89069). Foram registradas 22 espécies vegetais, com predominância de herbáceas. As estruturas de bambu permaneceram estáveis, consorciadas à vegetação introduzida e regenerada, evidenciando o sucesso da técnica. Apesar da baixa sobrevivência das espécies implantadas, a Engenharia Natural demonstrou-se eficaz no controle da erosão fluvial e o uso de bambu como material estrutural mostrou potencial promissor para projetos de recuperação de áreas degradadas.
*Palavras-chave***:** *Acrostichum aureum,* Bioengenharia, *Hibiscus tiliaceus*, Restauração Ecológica, PRAD.

Abstract

Erosion caused by *Bambusa tuldoides* Munro and the absence of native vegetation along the banks of the Camboriú River, in the Raimundo Gonçalez Malta Municipal Natural Park, prompted the application of Natural Engineering techniques for its containment. The intervention involved reshaping the slope (to 50°) and installing four bamboo Live Cribwalls (4 m² each), filled with clayey soil, to support the planting of *Hibiscus tiliaceus* L. (live stakes) and *Acrostichum aureum* L. (seedlings). A permeable bamboo fence was constructed to reduce the impact of boat-generated waves. To assess the effectiveness, a nearby control area with similar conditions, but without intervention, was monitored. Soil accumulation was observed in the treated area, while erosion worsened in the control area. The rooting rate of *H. tiliaceus* in the nursery was 42.5%; field survival rates were 9% for rooted stakes and 8% for non-rooted stakes. *A. aureum* showed a survival rate of 20%. Average vegetative cover on the Live Cribwalls was 20%, with no significant difference between the upper and lower sections (t=0.13793; p=0.89069). A total of 22 plant species were recorded, predominantly herbaceous. The bamboo structures remained stable over time, supporting both the introduced and regenerating vegetation, evidencing the success of the technique. Despite the low survival rates of the planted species, Natural Engineering proved effective in controlling riverbank erosion, and the use of bamboo as a structural material demonstrated promising potential for ecological restoration projects in degraded areas.
Keywords: Acrostichum aureum, Biotechnical Engineering, *Hibiscus tiliaceus*, Ecosystem Restoration.

INTRODUCTION

Natural Engineering has been employed in Europe for over 150 years as a method for restoring degraded environments. After World War II, however, rapid advancements in the technology of materials and equipment for earthwork and stabilization caused these techniques to fall into relative obscurity (DURLO; SUTILI, 2014). It was not until the 1950s that Natural Engineering techniques were extensively reintegrated as a critical tool for slope stabilization (ARAÚJO *et al.*, 2019).

Natural Engineering, or Bioengineering involves the use of natural raw material to minimize environmental problems related to soil erosion processes (SARTORI; RABBIT, 2023). The raw material may be inert and/or biological in nature (plants, plant parts, trunks, rocks, soil, etc.), thus utilizing the natural properties of vegetation for soil stabilization. In this process, the root systems assist in soil stabilization and aggregation, while decaying vegetation facilites water infiltration, thereby preventing erosion (CALVANI *et al.,* 2019). The methodology is characterized by low cost in relation to traditional engineering, with lower installation costs, high efficiency, and the possibility of being performed by local communities. Moreover, its techniques can be divided into superficial (up to 10 cm deep), stabilization (10-40 cm deep), and consolidation (40-220 cm deep), with the superficial level being the least complex (DURLO; SUTILI, 2014).

Natural Engineering can be a highly effective for restoring protected areas, as it mitigates the risks generated by soil erosion (PEPE *et al.*, 2020). This situation is observed at the Raimundo Gonçalez Malta Municipal Natural Park in Balneário Camboriú, SC, situated along the Camboriú River. In this case, a section of the park's slope was compromised by the exotic species *Bambusa tuldoides* Munro. (bamboo), resulting in erosion that damaged the visitation trail. Near this area, there is also the predominance of *Hibiscus tiliaceus* L. (coastal cottonwood) and *Acrostichum aureum* L. (mangrove fern), which indicates the potential of these species for area restoration efforts.

Hibiscus tiliaceus L. belongs to the Malvaceae family and *Achrosticum aureum* belongs to the Pteridaceae family, both of which are cosmopolitan and endemic to the tropical and subtropical regions. The first species is characterized by a root system that spreads near the soil surface with few primary roots, and its main form of propagation is through the cutting of live branches, or staking (ALURI *et. al.*, 2020). In contrast, the second species has the ability to withstand partial immersion, caused by tidal fluctuations, which accounts for its abundance in mangrove environments (ZHANG *et. al.*, 2016).

The species *Bambusa tuldoides* Munro, belonging to the Poaceae family, originates from China and is characterized by a pachymorph rhizome with a tufted habit. It reaches medium size (up to 17 m in height and 5 cm in diameter) and is commonly used in rural areas for light construction, plant crop protection, and erosion control, as its morphology features spreading rhizomes (BRAND *et al.*, 2020). Although bamboos are often used for soil stabilization, the species in question, because it has clumping and shallow rhizomes, eventually increases the erosion process, as the culms act as levers and the weight of the clumps weakens the soil (DURLO; SUTILI, 2014). In addition, boat-generated traffic was observed in the area, and the waves created by this movement remove material from the slope below the clumps, which further increases erosion.

Considering that no studies in the literature have identified the combination of these three plant species for the purpose of restoring areas with Natural Engineering, this work sought to fill this knowledge gap by investigating whether *Bambusa tuldoides* could serve effectively as inert material and whether *Hibiscus tiliaceus* and *Acrostichum aureum* would perform well when associated with bamboo as a physical structure. To answer these questions, this study aimed to evaluate a restoration project using the exotic species *B. tuldoids* as inert material and the native species *H. tiliaceus* and *A. aureum* as living material, based on the case study of the implementation of the Natural Engineering system in Raimundo Malta Park.

MATERIALS AND METHODS

The project was implemented inside the Conservation Unit of the Raimundo Gonçalez Malta Municipal Natural Park, in the municipality of Balneário Camboriú, state of Santa Catarina, Brazil.

Climate in the municipality of Balneário Camboriú, where the park is located, is classified as humid subtropical (Cfa), according to the methodology of Köppen. It is characterized by the influence of cold fronts throughout the year and by hot summers, with the highest temperatures registered in January and February. Mean annual temperature in the region is 19.5°C. The soil in the study area consists of Fluvial Neosol, typically alluvial, as it is formed by sediments carried from distant locations by river transport and deposited through tidal variation. The plant physiognomy of the area is Dense Ombrophilous Alluvial Forest, associated with the Pioneer Formation with Fluvial-Marine Influence (mangrove), characterized by the presence of riparian vegetation along the watercourse and by the periodic effects of river flooding.

Natural Engineering techniques were implemented on a riverbank slope with an approximate area of 25 m2 (2.5 m × 10 m), corresponding to a section of the left margin (upstream-downstream) of the Camboriú River.

Project Implementation and Maintenance

The project was developed after field visits for area reconnaissance and measurement, based on the techniques proposed by Durlo and Sutili (2014) and Araújo *et al.* (2019) for the restoration of degraded areas. The riverbank slope had an approximate height of 2.15 m and a slope greater than 90°, configuring an unstable and unsuitable condition for the establishment of the native vegetation. Given this scenario, the Live Cribwall ("Grade Viva", in Portuguese) technique was adopted, classified as a consolidation structure for bank stabilization.

To construct the Live Cribwall consolidation structure, the following species were used as natural material: *B. tuldoids* (exotic) as inert material, *H. tiliaceus* (native) and *A. aureum* (native) as living material.

H. tiliaceus was introduced by means of plant propagation using stakes obtained from semi-woody branches (DURLO; SUTILI, 2014). The stakes were collected from individuals of the species that occur naturally on the park's uneroded shores in the late summer and early fall/winter. The age of the individuals that served as plant material was not monitored, but collection was limited only to the semi-woody portions. The stakes that underwent a rooting period in a nursery were placed in ten-liter plastic bags with approximately 500g substrate (fertilized soil produced in the park's nursery) and stored in a greenhouse for around two months. The greenhouse was covered by a shade cloth (roof and sides), where the stakes were irrigated automatically twice a day.

Acrostichum aureum was introduced at the base of the slope, forming a barrier. The individuals were transplanted from the sampling area on the uneroded margins of the park to the project implementation area, maintaining a spacing of 50 cm between individuals.

Prior to project implementation (August/2018 to January/2019), boat-driven traffic was observed in the area. Therefore, to protect the slope and vegetation from this movement, a permeable physical barrier (fence) was constructed along the portion closest to the river. The barrier was approximately 14 m long and 1.2 m high, constructed using the bamboo. For the barrier, bamboo culms were cut into 2 m-long stakes and buried 0.5 m apart, to a depth of 0.8 m below the soil surface, resulting in a 1.2 m-high barrier. To strengthen the barrier, culms approximately 10 meters in length were stacked and tied to the stakes with #18 galvanized wire (1.24mm).

After the bamboo fence was installed, the slope gradient was adjusted to approximately 50º. Durlo and Sutili (2014) define this slope as ideal for implementing the Live Cribwall consolidation technique. The adjustment was made using soil and trunks to fill a cavity (approximately one meter deep) at the base of the slope. To build the Live Cribwall, first the bamboo culms were cut into 20 sections 2.5 m long and another 36 sections 2 m long. Subsequently, the sections were used to assemble the four structures (2.5 m x 2 m), each of which was subdivided into 32 parts (25 cm x 50 cm). The cribwall sections were joined with #18 galvanized wire approximately 50 cm in length at each intersection. Once built, the fences were positioned on the adjusted slope and filled with soil (approximately 7 m^3). In each Live Cribwall, eight stakes of *H. tiliaceus* were placed in the subdivisions. The stakes were approximately 40 cm long.

Project Evaluation

After the technique was implemented, in March/2019, the project was monitored monthly, for ten months. On each monitoring day, together with the evaluation, the necessary maintenance was carried out to support the ongoing restoration. Hibiscus individuals that did not survive were replaced and classified into planting (month) and moment (1, 2, 3, n, ...). Moreover, solid waste carried by the river and deposited in the area was removed.

In addition to the project implementation area, a neighboring control area was selected with the same characteristics as the area where the Natural Engineering technique was not applied. In both areas, the establishment of *B. tuldoides* and soil erosion on the slope were observed. Before implementing the restoration project, four bamboo stakes were buried along the riverbanks: two in the front portion of the Contal Area and two in front of the designated project area, aligned with each other. One of the stakes was positioned away from the slope and another immediately in front of the slope. A laser tape measure (Bosh DLE70) was positioned on the furthest stake and used to determine the distance between the stake closest to the slope and the soil surface immediately upslope from it. Erosion was measured monthly using a laser tape measure, in both areas, from August/2018 to December/2019. Due to the variation in the level of the Camboriú River caused by tidal effects, it was not possible to calculate the volume of eroded material. Therefore, the surface affected by erosion was estimated from the variation distance between the measurement stake and the slope.

The effectiveness of natural bamboo material as inert raw material for Natural Engineering technique was evaluated for durability using photographic records of the same area over time. In addition, the presence of fungi and xylophageal organisms was monitored (NURDIAH, 2016).

The introduced plant species (hibiscus and mangrove fern) was evaluated using survival rate (1), calculated at the end of the tenth month of monitoring (December/2019) and rooting rate in a greenhouse (2):

$$TS = \frac{(Nf \times 100)}{No} \quad (1)$$

Where: TS = survival rate (%); No. = initial number of stakes planted; Nf = the final number.

$$TE = \frac{(Nf \times 100)}{No} \quad (2)$$

Where: TE = rooting rate (%); No. = initial number of stakes; Nf = the number of stakes that formed roots and/or calluses.

The growth of the introduced *H. tiliaceus* individuals was evaluated using biometric parameters (height and number of leaves) and a centimeter-graded measuring tool (Lufkin 50m). In turn, natural regeneration was evaluated using the quadrant methodology (1 m^2). To facilitate counting, they were subdivided into 100 units of 0.01 m^2, so each unit corresponded to 1% of soil vegetation cover. The quadrants were systematically arranged at the upper and lower sections on the left, in each of the four live fences (N=8). The percentage of soil vegetation cover was calculated (CAUSTON, 1988), as well the species involved in regeneration. Soil vegetation cover data were submitted to the t-Student Test (Paleontological Statistics software – PAST/ v. 3.25) to assess whether there were significant differences between the upper half (N=36) and lower half (N=36) of the Live Cribwall.

REVISTA FLORESTA
Engenharia Florestal
ISSN 1982-4688
Edição 56
Universidade Federal do Paraná
Setor de Ciências Agrárias

RESULTS

The erosive process in both the control and project areas was evaluated for 17 months. The results revealed distinct behaviors, with an intensification of erosion in the control area and a reduction of erosion in the project area, as illustrated in Figure 1.

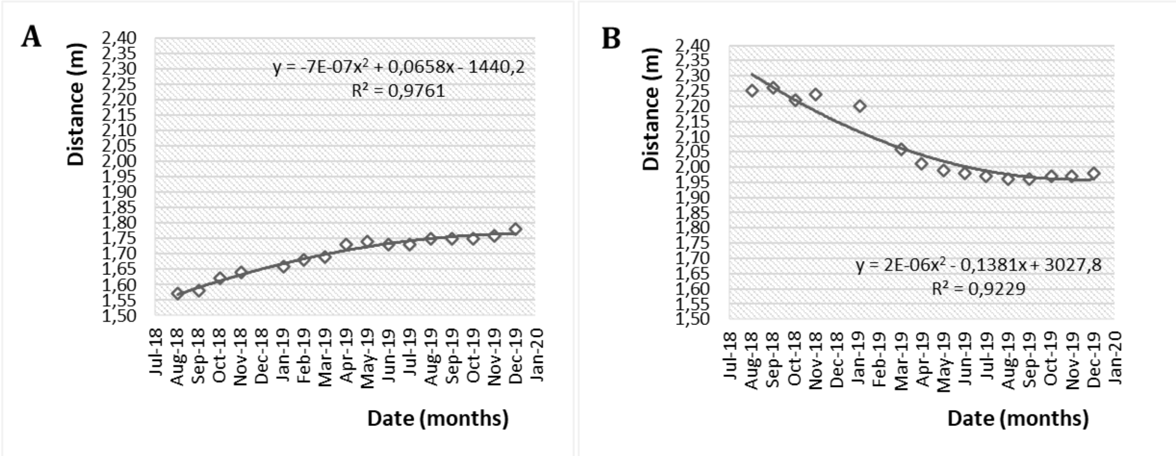

Figure 1: Erosion in the control area (A); erosion in the project area (B) before (August/2018 to January/2019) and after implementation (March/2019 to December/2019). Distance (m) between the demarcation stake and the slope, per month of monitoring.

Figura 1: Processo erosivo na área controle (A), a esquerda; processo erosivo na área do projeto (B) anteriormente (agosto/2018 a janeiro/2019) e após implantação (março/2019 a dezembro/2019). Distância (m) entre a estaca de demarcação e o talude, por mês de monitoramento.

Regarding the durability of the physical structures, no structural degradation was observed in the Live Cribwall from April/2019 to December/2019 due to decomposition. The bamboo structure retained its physical integrity, showing only a slight change in coloration to light gray tones.

With regard to vegetation cover, there was a 15% increase in the average compared to the first month of sampling (Figure 2), with an increase in cover from September/2019. No significant differences (*t*= 0.13793 p= 0.89069) were observed between the upper (N=36) and lower (N=36) sections of the Live Cribwalls.

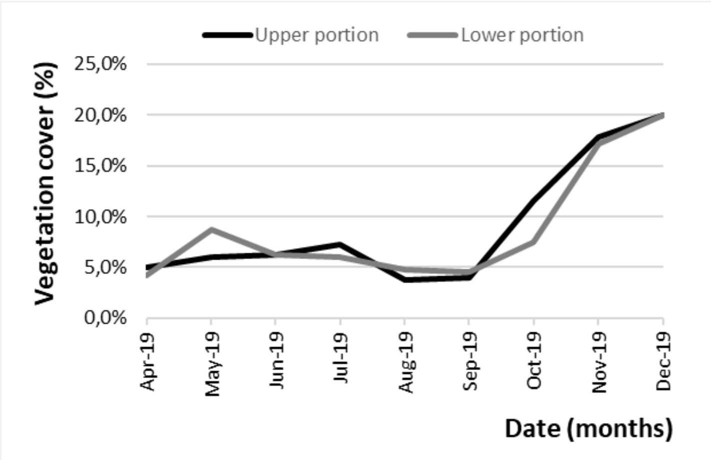

Figure 2: Average percentage (%) of soil vegetation cover per month between the upper and lower sections in the project area.

Figura 2: Porcentagem (%) média de cobertura vegetal do solo por mês entre a porção superior e inferior na área do projeto.

Regarding natural regeneration, by the end of the final sampling month, 22 plant taxa (Table 1) were identified in the project area, comprising 20 individuals identified to species level (90.90%), one to family level (4.54%), and one individual that remained unidentified (4.54%). Of the taxa identified: 16 were herbaceous (72.72%), three were shrubby (13.63%), one was arboreal (4.54%) and one was scandent (4.54%). In terms of origin, 15 were native species (68.18%), two were exotic (9.09%), three were naturalized (13.63%) and two were unidentified (9.09%).

Table 1: List of the 22 plant taxa recorded from natural regeneration sampling. The table presents data on family, species, common name, origin, and growth habits of the sampled individuals.
Tabela 1: Lista dos 22 táxons vegetais obtidos a partir da amostragem da regeneração natural. A tabela apresenta os dados de família, espécie, nome popular, origem e hábito dos indivíduos amostrados.

Family	Scientific name	Common name	Origin*	Habit
Apiaceae	*Hydrocotyle bonariensis* Lam.	Largeleaf pennywort	N	herbaceous
	Apium leptophyllum (Pers.) F. Muell. ex Benth.	Wild celery	N	herbaceous
Asteraceae	*Youngia japonica* (L.) DC.	Asian hawksbeard	E	herbaceous
	Emilia fosbergii Nicolson	Cupid's-shaving-brush	N	herbaceous
	Sphagneticola trilobata (L.) Pruski	Wedelia	N	herbaceous
Commelinaceae	*Commelina erecta* L.	Whitemouth dayflower	N	herbaceous
Cyperaceae	*Cyperus esculentus* L.	Yellow nutsedge	Na	herbaceous
	Cyperus ia L.	Rice flatsedge	N	herbaceous
Denstaedtiaceae	*Pteridium aquilinum* (L.) Kuhn	Bracken	N	herbaceous
Fabaceae	NI	NI	-	NI
Hypoxidaceae	*Hypoxis decumbens* L.	Goldstar	N	herbaceous
Lamiaceae	*Aegiphila integrifolia* (Jacq.) Moldenke	Entireleaf spiritweed (Tamanquiero)	N	arboreal
Malvaceae	*Hibiscus tiliaceus* L.	Sea hibiscus	N	shrubby
	Sida rhombifolia L.	Arrowleaf sida	N	herbaceous
	Hibiscus rosa-sinensis L.	Chinese hibiscus	E	shrubby
	Malvastrum coromandelianum Garcke	Threelobe false mallow	N	herbaceous
Melastomatacea e	*Tibouchina urvilleana* (DC.) Cogn.	Princess flower	N	shrubby
Oxalidaceae	*Oxalis corniculata* L.	Creeping woodsorrel	Na	herbaceous
	Oxalis latifolia Kunth	Broadleaf woodsorrel	Na	herbaceous
Phyllanthaceae	*Phyllanthus tenellus* Roxb.	Long-stalked leaf-flower	N	herbaceous
Pteridaceae	*Acrostichum aureum* L.	Mangrove fern	N	herbaceous
NI	NI	NI	-	scandent

*Native = Na; Exotic = E; Naturalized = Na

Figure 3 shows data on number of species and total number of individuals sampled from March/2019 to December/2019. Between May/2019 and September/2019, only three new species were identified and the total number of individuals sampled did not exceed 60 (compared to 167 total individuals recorded in December/2019). Starting in September/2019, the number of individuals increased considerably, whereas only four new species were identified, indicating dominance by a particular taxon.

REVISTA FLORESTA Engenharia Florestal
ISSN 1982-4688
Edição 56
Universidade Federal do Paraná
Setor de Ciências Agrárias

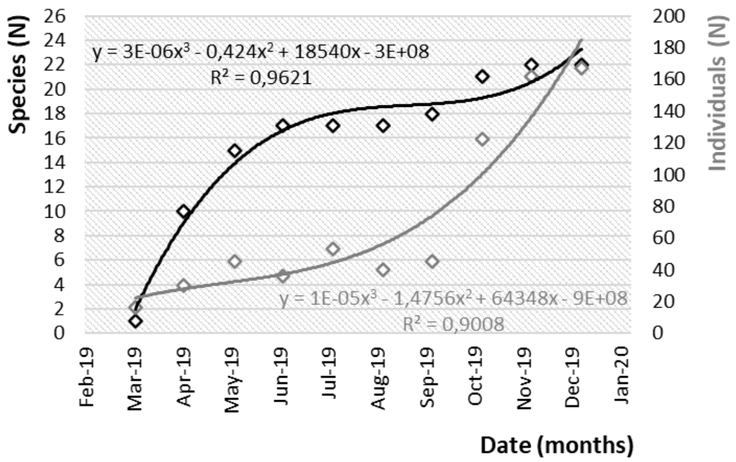

Figure 3: Number of species (N) in relation to total number of individuals (N) per sampling month (March/2019 to December/2019).

Figura 3: Número de espécies (N) em relação ao número total de indivíduos (N) por mês de amostragem (março/2019 a dezembro/2019).

After the 10-month period (March to December 2019), the rooting rate of the individuals of *H. tiliaceus* maintained in the greenhouse was 42.5%; however, no result was recorded for *A. aueam*, as this species was not used for staking. The survival rate for both species over the same 10-month monitoring period was low: 9% for rooted and 8% for non-rooted *H. tiliaceus* stakes and 20% for *A. aureum* .

Table 2 shows the values recorded for the nine surviving individuals of *H. tiliaceus* at the end of 10-month monitoring period (March/2019 to December/2019). The surviving individuals showed increases in height and leaf number, indicating growth, especially for the survivors of the first moment (1r), implemented in March/2019. Individual 16 showed no increase in height, while individual 11 exhibited a reduction in height along with leaf loss. Of the non-rooted stakes, only two of the second moment (2s) survived and both showed modest growth, as evidenced by the difference in leaf number between the start and end of monitoring.

Table 2: Growth of introduced hibiscus classified as: cutting, planting (month), moment (1, 2, n, ...), position (upper/lower), start height (ho), end height (hf), number of leaves (start and end).

Tabela 2: Crescimento dos hibiscos introduzidos, classificados em: estaca, plantio (mês), momento (1, 2, n, ...), posição (superior/inferior), altura incial (ho), altura final (hf), número de folhas (inicial e final).

Stake	Planting (month)	Moment*	Position	ho (cm)	hf (cm)	no. leaves (start)	no. leaves (end)
2	Mar/19	1r	lower	68	92	15	29
23	Mar/19	1r	lower	64	72	13	22
9	May/19	2r	upper	5	33	0	6
8	Sept/19	4s	lower	15	17	0	13
16	Sept/19	4s	lower	20	20	0	6
6	Oct/19	5r	lower	18	26	4	6
11	Oct/19	5r	upper	23	18	5	3
19	Oct/19	5r	upper	28	30	8	9
21	Oct/19	5r	lower	16	25	4	9

**r=rooted / s=non-rooted*

Regarding fauna interactions with the implanted system, the monitoring period revealed herbivory by Lepidoptera on hibiscus stakes, including pupae on the abaxial leaf surface; xylophagy by termites on hibiscus stakes without affecting the bamboo structure; and carcinofauna activity, evidenced by burrows of individuals of *Uca* sp. in the lower portion of the live fence.

In general, the visual quality of the landscape noticeably improved with project implementation (Figure 4).

Figure 4: Temporal evolution of the vegetation cover in the restoration area. The image on the left shows the study area before project implementation, August/2018. The image on the right shows the implemented project after ten months of monitoring, December/2019. Source: Author.

Figura 4: Evolução temporal da área em recuperação. A imagem da esquerda evidencia a área de estudo antes da implantação do projeto, no mês de agosto/2018. A imagem da direita evidencia o projeto implantado e após o décimo mês de monitoramento, em dezembro/2019. Fonte: Autor.

DISCUSSION

In the control area, the distance from the demarcation stake to the slope increased, indicating an ongoing erosive process with continued progression over time. Thus, intervention through a restoration project was necessary. In the project area were the Natural Engineering technique was applied, the distance from the demarcation stake to the slope varied during the pre-implementation months (August/2018 to January/2019). The cavity identified during stake adjustment contributed to distance reduction, caused by a river erosion effect. In contrast, the increase in distance can also be explained by the effect of surface soil erosion.

After project implementation (February/2019), the distance from the demarcation stake to the slope decreased, indicating soil accumulation in the area with a continuing tendency. The reduced erosion in the project area where Natural Engineering technique was applied can be attributed to the introduced structures, fulfilling part of the restoration objectives as reported by Durlo and Sutili (2014) and Araújo *et al.* (2019), in contrast to the control area.

Given the proximity of the area to a watercourse, the soil is hydromorphic, composed of sandy sediments and organic matter with a silty character, highly susceptible to erosion due to an unfavorable infiltration/runoff ratio (SILVA et al., 2020). Since the control and project areas are close, they respond similarly to rainfall events. Thus, the erosion observed in the control area can be primarily associated with soil characteristics, in addition to rainfall intensity. Furthermore, the absence or scarcity of vegetation cover probably contributed to the intensification of erosion. The presence of material covering the soil significantly reduces particle removal by pluvial erosion (SANTOS et al., 2009; SOUZA et al., 2018). According to Silva et al. (2024), vegetation cover practically eliminates soil loss and erosion decreases with greater vegetation density regardless of rainfall levels (mm).

Regarding the integrity of the bamboo structures, humidity affects durability primarily through fungal activity. However, even in direct contact with the soil, bamboos can take up to three years to decompose (JANSSEN, 2000). Moreover, the presence of fungi may have caused the change in color, but without affecting the structure. Xylophagous insects were not observed, despite their presence on the plant stake, indicating either material resistance or lack of attractiveness as food or insect shelter.

Many bamboo species can be used in construction due to their excellent physical-mechanical properties (NURDIAH, 2016), especially the species *Bambusa tuldoides* for its lightness and high rigidity. In this regard, the lightness of the bamboo facilitated both construction and installation of the structures, while the rigidity enhanced material resistance to weathering, as well as to fungal and insect attacks, over the monitoring period (February/2019 to December/2019). After ten months of implementation, the structures were still intact and integrated with both introduced and regenerated vegetation, indicating overall success of the techniques. Thus, the bamboo species proves effective for Natural Engineering applications.

The more pronounced increase in vegetation cover from September onward is associated with temperature effects on plant growth, since lower winter temperatures reduce physiological functions (CARVALHO *et al.*, 2022). This abiotic factor likely contributed to lower vegetation cover from April/2019 to August/2019 and, therefore, degraded area restoration projects should account for climatic conditions and be implemented during periods that favor plant growth.

The absence of differences between treatments, that is, the similar vegetation cover percentages between the upper and lower sections of the Live Cribwalls, may have resulted from their function as a physical barrier. This shield minimized the effects of increased flow, river level variations, and boat-driven traffic, and especially protected the slope base where water would otherwise reach without the barrier.

The herbaceous species were the most abundant and the first to colonize the area. These species are common ecological pioneers in restoration areas and are widely recommended for restoring degraded areas. In addition to providing good vegetation cover, their root systems increase soil protection against surface and wind erosion, thereby facilitating ecological succession (CALVANI *et. al.*, 2019). These authors also highlight the importance of woody species, which have a deeper root system than herbaceous vegetation and are effective in containing and mitigating shallow erosive processes. Although scrub species were not highly representative in the project area, they are characterized by this type of root system.

The increase in the number of individuals and reduction in species richness observed from September/2019, together with the dominance of certain taxa, were expected, as the area was in the initial process of regeneration and colonized mainly by pioneering species. In this regard, Forest, Drezza *et al.* (2022) found that only ten species accounted for 50% of total individuals in the Atlantic Forest of southern Brazil, within the plant physionomy of the Mixed Ombrophilious. Although the plant physiognomy is different in the project area, this result reinforces that the dominance of a few species is a common pattern in early stages of regeneration. In the aforementioned study, this configuration was associated with forest fragmentation, a factor that intensifies edge effects, reduces genetic variability, and favors the establishment of opportunistic species.

The lower rooting rate values (42%) observed for individuals of *H. tiliaceus*, in comparison with those reported in the literature for the same genus, *Hibiscus*, can be attributed to differences in experimental conditions. Studies conducted in a controlled laboratory environment, such as those by Pizzato *et al.* (2011) and Souza *et al.* (2015), showed rooting percentages of 70% and 75%, respectively, indicating greater efficiency under these conditions. The present study, in turn, was conducted in a greenhouse, in late summer and early fall. Differences in environmental conditions, such as lower temperatures, which directly affect the physiological functions of plants (CARVALHO *et al.*, 2022), may explain the lower rooting rate observed. Prasad *et al.* (2012) evaluated the rooting of living stakes of *H. tiliaceus* in slopes composed of residual sandy soils in a tropical region of Malaysia and found that the species can be used efficiently in the stabilization of erosive processes.

Despite the low survival rate observed in this study for hibiscus, the literature indicates that the species performs well in terms of the survival of planted individuals, which helps improve landscape quality (LIU *et al.*, 2014), and has a high capacity for natural regeneration, often showing dominance in this respect in degraded areas (PRABAKARAN; PARAMASIVAN, 2014). According to Liu *et al.* (2014), the species has medium tolerance to shading. In this context, the shading generated by the remaining bamboo in the area adjacent to the project may have negatively influenced species development.

The survival rate for the introduced species was low, both for the rooted and non-rooted stakes of *H. tiliaceus* and for *A. aureum*. However, it is important to highlight that the use of the species *A. aureum* (mangrove fern) is unprecedented, as the literature does not provide studies in which the survival of these individuals has been monitored, whether occurring naturally or introduced in vegetation restoration projects.

Nakata *et al.* (2016), using mixed planting of different tree species combined with bamboo structures, reported a 90% survival rate, which is higher than the value observed in the present study. The low survival rate recorded may be associated with the dry period (from April to August), as well as the quality of the introduced soil, although this was not evaluated. Factors such as the lunar phases at the time of collection may have influenced the growth and establishment of the introduced plant species. Nevertheless, early signs of biotic interactions were observed.

Biotic interactions are an important indicator that restoration of the degraded area and ecosystem resilience are occurring (MCDONALD *et al.*, 2016). These interactions in the study area do not seem to have influenced the results of the project, especially considering the short monitoring period. However, the absence of termite attacks on the physical structure indicates the potential effectiveness of bamboo as a material.

Finally, the positive visual effect on the landscape of the area should be highlighted. Previously, this area showed clear signs of erosion and was dominated by exotic vegetation (Figure 4), despite being located in a Conservation Unit. This condition contradicts the objectives of the Park category, which include the preservation of ecosystems and scenic beauty, in addition to the status of the area as a Permanent Preservation Area (APP) due to its location along a watercourse. According to Portela *et. al.* (2021) alterations to waterways lead to changes such as geomorphic simplification and reduced habitat heterogeneity; contraction of the floodplain; decreased social value of the area, making it less attractive for recreational purposes; and ecological simplification (a decline in biodiversity and impaired ecosystem functioning). This series of impacts reinforces the importance of restored environments along the margins of waterways.

CONCLUSIONS

- The main contribution of this study lies in the novel use of *Acrostichum aureum* (mangrove fern), as no studies were identified that evaluate the survival of such individuals, either in natural occurrence or when applied in the restoration of degraded areas.
- Morever, the species *Bambusa tuldoides* (bamboo) proved to be resistant and easy to manage as a cribwall in the restoration of river slopes. The technique can be applied in other areas of the park or in similar settings with problems related to soil erosion and where the occurrence of exotic species must be reduced or eradicated for the subsequent replacement with native species.
- Vegetation associated with physical structures is a fundamental premise of Natural Engineering, and the results of propagation methods using stakes are important for future studies, as research on this method is still limited.
- The natural regeneration of vegetation played an important role in protecting the soil against weathering, considering that the number of species colonizing the area is expected to increase over time.
- The presence of fauna is an important indicator of environmental restoration; however, the monitored period did not allow verification of biotic interactions such as pollination and seed dispersal, which would provide stronger evidence of the project's success.

REFERENCES

ALURI, J. S. R.; KUNUKU, V. R.; CHAPPIDI, P. R.; KAMMARCHEDU, B. J. P. Pollination ecology of Hibiscus tiliaceus L. (Malvaceae), an evergreen tree species valuable in coastal and inland eco-restoration. **Transylvanian Review of Systematical and Ecological Research**, v. 22, n. 2, p. 47-56, 2020.

ARAÚJO, G. H. S.; ALMEIDA, J. R.; GUERRA, A. J. T. **Gestão ambiental de áreas degradadas.** 13. ed. Rio de Janeiro: Bertrand Brasil, 2019.

BRAND, M. A.; GAA, A. Z. N.; SOUZA JUNIOR, A. S.; CUNHA, A. Potencial do uso de quatro espécies de bambu para a produção de carvão vegetal para uso doméstico. **Ciência Florestal**, v. 30, n. 1, p. 60-71, 2020.

CALVANI, G.; FRANCALANCI, S.; SOLARI, L. A physical model for the uprooting of flexible vegetation on river bars. **Journal of Geophysical Research**, v. 124, n. 4, p. 867-1053, 2019.

CARVALHO, C. G. I.; SANTOS, M. L.; VIEIRA, L. R.; LOPES, A. M.; CARMONA, P. A. O.; SOUSA, C. A. F.; SOUZA JUNIOR, M. T. Morphophysiological responses of Setaria viridis to cold stress. **Pesquisa Agropecuária Brasileira**, v. 57, e02424, 2022.

CAUSTON, D. R. **An introduction to vegetation analysis: principles and interpretation.** London: Unwin Hyman, 1988.

DREZZA, T. R.; MASTELLA, A. D. F.; SCHNEIDER, C. R.; PALMA, V. H.; SCHIMALESKI, A. C. C.; SOUZA, K. K. F.; KRATZ, D.; ANGELO, A. C. Composição, estrutura e dinâmica da regeneração natural ao longo de 18 meses de estudo em sub-bosque de Pinus elliottii Engelm. **Research, Society and Development**, v. 11, n. 8, e33311830016, 2022.

DURLO, M. A.; SUTILI, F. J. **Manejo biotécnico de cursos de água.** 3. ed. Santa Maria: Dos Autores, 2014.

JANSSEN, J. J. A. **Designing and building with bamboo.** China: International Network for Bamboo and Rattan (INBAR), 2000. (Technical Report, n. 20).

LIU, X.; LU, Y.; XUE, Y.; ZHANG, X. Testing the importance of native plants in facilitating the restoration of coastal plant communities dominated by exotics. **Forest Ecology and Management**, v. 322, p. 19-26, 2014.

MCDONALD, T.; GANN, G. D.; JONSON, J.; DIXON, K. W. **International standards for the practice of ecological restoration: including principles and key concepts.** Washington: Society for Ecological Restoration, 2016.

NAKATA, A. A. M.; NUNES, J. O. R.; JULIAN, C. Aplicação de bioengenharia para recuperação de uma voçoroca provocada por erosão hídrica, localizada no distrito de Amadeu Amaral, Marília – SP. **Colloquium Exactarum**, v. 8, n. 3, p. 13-20, 2016.

NURDIAH, E. A. The potential of bamboo as building material in organic shaped buildings. **Procedia - Social and Behavioral Sciences**, v. 216, p. 30-38, 2016.

PEPE, G.; BAUDINELLI, E.; ZANINI, M.; CALCATERRA, D.; CEVASCO, A.; SCARPELLINI, P.; FIRPO, M. Application of bioengineering techniques as geo-hydrological risk mitigation measures in a highly valuable cultural landscape: experiences from the Cinque Terre National Park (Italy). **Sustainability**, v. 12, n. 20, p. 1-22, 2020.

PIZZATTO, M.; WAGNER JÚNIOR, A.; LUCKMANN, D.; PIROLA, K.; CASSOL, D. A.; MAZARO, S. M. Influência do uso de AIB, época de coleta e tamanho de estaca na propagação vegetativa de hibisco por estaquia. **Revista Ceres**, v. 58, n. 4, p. 487-492, 2011.

PORTELA, A. P.; VIEIRA, C.; CARVALHO-SANTOS, C.; GONÇALVES, J.; DURANCE, I.; HONRADO, J. Regional planning of river protection and restoration to promote ecosystem services and nature conservation. **Landscape and Urban Planning**, v. 211, 104101, 2021.

PRABAKARAN, N.; PARAMASIVAM, B. Recovery rate of vegetation in the tsunami impacted littoral forest of Nicobar Islands, India. **Forest Ecology and Management**, v. 313, p. 243-253, 2014.

PRASAD, A.; KAZEMIAN, S.; KALANTARI, B.; HUAT, B. B. K.; MAFIAN, S. Stability of tropical residual soil slope reinforced by live pole: experimental and numerical investigations. **Arabian Journal for Science and Engineering**, v. 37, p. 601-618, 2012.

SANTOS, T. E. M.; MONTENEGRO, A. A. A.; PEDROSA, E. M. R. Características hidráulicas e perdas de solo e água sob cultivo do feijoeiro no semiárido. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 13, n. 3, p. 217-225, 2009.

SARTORI, M. A.; COELHO, G. T. C. P. Utilização de indicadores biológicos e uso de retentores de sedimentos na restauração florestal e recuperação de áreas degradadas. **Revista Maestria**, v. 18, p. 67-76, 2023.

SILVA, T. P.; NACHTIGALL, S. D.; NUNES, M. C. M.; LIMA, C. L. R.; KNAPP, A. P. Modeling of water erosion in a sub-basin in Rio Grande do Sul using the RUSLE model. **Revista Engenharia na Agricultura**, v. 28, p. 302-313, 2020.

SILVA, C. M.; BRITO, L. G.; SILVA, M. M. A.; CARVALHO, A. Quantification of water, soil and nutrient losses in the Farinha river basin, Carolina – MA, in the Cerrado biome. **Caderno Pedagógico**, v. 21, n. 5, p. 1-24, 2024.

SOUZA, R.; CAVALCANTE, M. Z. B.; LIMA, M. P. D.; ALIXANDRE, T. F.; NASCIMENTO, R. T. Vegetative propagation of hibiscus with different types of cuttings and IBA concentrations. **Comunicata Scientiae,** v. 6, n. 3, p. 1-7, 2015.

SOUZA, T. E. M. S.; PEREIRA, E. G.; PEREIRA, D. S.; SANTOS, L. M. Reducing erosion in sorghum crops with mulching. **Revista Caatinga**, v. 31, n. 3, p. 730-736, 2018.

ZHANG, Z.; HE, Z.; XU, S.; LI, X.; GUO, W.; YANG, Y.; ZHONG, C.; ZHOU, R.; SHI, S. Transcriptome analyses provide insights into the phylogeny and adaptive evolution of the mangrove fern genus Acrostichum. **Scientific Reports**, v. 6, 35634, 2016. DOI: 10.1038/srep35634.