

## Dispersal of the brachiaria invasive species in a tropical estuary

### *Dispersão da espécie invasora braquiária em um estuário tropical*

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**Abstract:** Excess nutrients in estuaries favor the growth of aquatic plants. Invasive plants, such as brachiaria (*Urochloa arrecta*), increase competition, compromising native species survival and causing ecological imbalance. This study examined the spread of brachiaria in the Guaraguaçu River estuary in Paraná, Brazil, in two scenarios (rainy and dry), considering flow and salinity variations. The brachiaria spread was evaluated using a Lagrangian transport model to simulate inert particle trajectories. Results indicate that in the rainy scenario (lower salinity), particles tend to move more easily out of the modeled domain. In the dry scenario (higher salinity), they tend to remain for over 30 days. These findings show the dynamics of species fixation and adaptation.

**Keywords:** Biological invasion; Salinity; Lagrangian transport.

**Resumo:** O excesso de nutrientes em estuários favorece o crescimento de plantas aquáticas. Plantas invasoras, como a braquiária (*Urochloa arrecta*), aumentam a competição no meio, dificultando a sobrevivência de espécies nativas e causando desequilíbrio ecológico. Este trabalho examinou a propagação da braquiária no estuário do rio Guaraguaçu em dois cenários (chuvoso e seco), considerando variações de vazão e salinidade. O espalhamento da braquiária foi avaliado pela simulação de trajetórias de partículas inertes, usando um modelo Lagrangeano de transporte. Os resultados mostraram que no cenário chuvoso (menor salinidade) as partículas tendem a sair mais facilmente do domínio modelado. No cenário seco (maior salinidade), tendem a permanecer por mais de 30 dias. Esses resultados demonstram a dinâmica de fixação e adaptação dessa espécie.

**Palavras-chave:** Invasão biológica; Salinidade; Transporte Lagrangeano.

## 1. Introduction

The Guaraguaçu River Estuary (GRE), an important tributary of the Paranaguá Estuarine Complex (PEC), is located in the southern region of Brazil, in the state of Paraná. This estuary is crucial for the local community, which depends on the river's multiple utilities, (SATO; ÂNGULO, 2023). The river mouth is near the Port of Paranaguá, Brazil's largest agricultural export terminal, essential for the region's economic activity.

Various aquatic plant species are found in this estuary, including *Urochloa arrecta* (Hack. ex T.Durand & Schinz) Morrone & Zuloaga, Bora (2019), also known as brachiaria. This species is a perennial aquatic nitrophilous grass with long floating branches that form thick mats of leaves, roots and stems (FERREIRA *et al.*, 2016; FARES, NONATO; MICHELAN, 2020). It is highly invasive, and its presence imbalances the local ecosystem for the native species. Moreover, it impairs navigability in some areas of the estuary.

In most cases, invasive species are introduced in a given environment by human actions that eliminate natural barriers and transport species accidentally (TEIXEIRA, 2015). These species are usually competitors in estuaries, with great potential to reduce diversity or even extinguish native species (MICHELAN *et al.* 2010; CARNIOTTO *et al.* 2013). The accelerated growth of invasive species can cause damage to public water supplies, leisure activities, fishing, navigation, and environmental aesthetics (TEIXEIRA, 2015).

The competition-to-stress hypothesis may be appropriate to explain the permanence and survival of species in estuarine environments (NUNES *et al.* 2018). It suggests that specific factors, such as salinity variation and flooding caused by tidal action in the lower estuary, exclude some species from different regions of the estuary. On the other hand, in the innermost areas, competition between species is a limiting factor for survival (CRAIN *et al.* 2004 and ENGELS *et al.* 2010).

Salinity variation in estuarine environments is directly related to river discharges and tides. When river discharges decrease during drought, saltwater intrusion tends to advance and increase the salinity of the water inside the estuary. This phenomenon can cause changes in the local fauna and flora, affecting the survival of salinity-sensitive species. Environmental modeling can be used to evaluate the extent and impact of the intrusion of saline waters by simulating salt concentrations in an estuary under different discharge scenarios and tidal periods.

Literature shows some studies dedicated to understanding the effects of saltwater intrusion on physiology and ecology: i) Bond-Lamberty *et al.* (2023) investigated the effects of saltwater intrusion on physiology and ecology in a mid-Atlantic coastal deciduous forest in the USA, documenting changes in specific leaf area (SLA) of trees in response to salinity exposure, and the results showed a significant reduction in SLA in trees exposed to more saline environments, corroborating the hypothesis that chronic salinity exposure alters leaf morphology in tree species; and ii) Wanga *et al.* (2020) verified the influence of hydrodynamics on the ecological processes of a system, observing the transport and destination of nutrients and phytoplankton blooms along gradients of salinity and turbidity in the St. Johns estuary. The results reveal seasonal and longitudinal patterns of phytoplankton, dissolved oxygen, and nutrients in the estuary. Notable declines in phytoplankton and dissolved oxygen concentrations in the freshwater-saltwater transition zone were also observed.

Variations in saline concentrations can affect biological communities. Therefore, analyzing this phenomenon allows measuring impacts on coastal ecosystems and helps to understand the behavior of species distribution in freshwater-saltwater transition zones. Other studies have investigated the relationship between the forcings' acting on coastal systems and the extent of saltwater intrusion, including Medeiros (2003), Silva *et al.* (2018), Sant'Ana (2023), and Lima (2016).

Environmental modeling of estuarine systems is a fundamental tool for understanding the different transport mechanisms within the estuary. In this sense, an integrated analysis of physical and chemical processes is crucial for understanding ecological processes (ELLIOT *et al.*, 2011).

Like other coastal regions, the GRE also suffers from the impacts of brachiaria invasion, which can alter the circulation and the water mixing processes in the area. The central hypothesis analyzed in this work is how the river water inflow and the consequent variations in saltwater intrusion influence the spread of brachiaria along the estuary. To this end, saline concentrations and particle transport in the estuary are analyzed as indicators of brachiaria presence. Therefore, this study aims to answer the following questions:

- (1) Do the brachiaria present in the GRE have the potential to reach regions outside of it?
- (2) How does brachiaria spread in the GRE under different river flow scenarios?
- (3) Do variations in salinity influence the establishment of the species?
- (4) What are the stagnant areas in the GRE, and how do they influence the spread of brachiaria?

## 1.1 Study Area

The Guaraguaçu River Basin (Figure 1) covers an area of 311.0 km<sup>2</sup>. Its drainage network comprises eight rivers. The rivers in the basin are tributaries of Guaraguaçu and Cambará, the largest rivers in length. They act as an ecological corridor and serve as the basis for the gene flow and health of various animal and plant communities (ELSTE, 2021).

The Guaraguaçu River plays a vital role in supplying the municipalities of Pontal do Paraná and Matinhos, with around 70,000 inhabitants (<https://cidades.ibge.gov.br/>; 2022 census), serving as a water source, receiving body, and effluent diluter for these municipalities. The Guaraguaçu Ecological Station is located in the basin, protecting the area around the river and allowing the recovery of the original ecosystem and the natural evolution of the region's native flora and fauna. As the river basin is near the mountain range Serra da Prata, the slopes vary between strongly undulating (20-45%), mountainous (45-75%), and steep (above 75%); in the plain region, the terrain is almost flat ( $\leq$  to 3%), and gently undulating (3-8%) (ELSTE, 2021). According to the Köppen climate classification (1928), the study area has a humid subtropical climate (Cfa), characterized by long, hot, and humid summers, with annual rainfall of 2,500 mm and 85% average relative humidity (ELSTE, 2021).

In the GRE, the water temperature changes seasonally, from 23° C to 30° C during summer and between 18° C and 25° C during winter (ELSTE *et al.*, 2021). Salinity varies at different times of the year: in rainy periods, such as December to March, salinity can reach a maximum of 15.0 psu at the confluence with PEC. In drier seasons, salinity varies between 10.0 and 20.0 psu at the mouth of the river (SANT'ANA, 2023). Feltrin *et al.* (2011) measured salinity in the Guaraguaçu River in 16 different locations from June 2005 to May 2006 and observed that salinity decreased in the river during the summer, which can be directly related to the fluvial input. A more significant river inflow during summer lowers the salt concentration. Given the low fluvial input, salinity is higher in the innermost regions during winter.

Bora (2019) and Contente *et al.* (2011) analyzed the salinity distribution in the Guaraguaçu River, associating it with biological aspects such as fish assemblages and abiotic factors. Both analyses indicated that the species studied depend on the water's saline concentration.

Regarding water quality, Elste *et al.* (2019) investigated the effects caused by the Pery River, a tributary of the Guaraguaçu River. The researchers found deficient levels of dissolved oxygen (0.56 mg/L) and high levels of phosphate (PO<sub>4</sub>) and ammonium (NH<sub>4</sub>) ions, highlighting the improper disposal of sanitary effluents into this river.

## 1.2 Spread of *Brachiaria*

*Brachiaria* can cause many effects on the environment, such as suppression of native vegetation, reduction in the diversity of aquatic communities, clogging of hydroelectric canals, and even clogging of water pipelines or blocking aqueducts (TEIXEIRA, 2015; FERREIRA *et al.* 2016; SATO *et al.* 2021; GALVANESE *et al.* 2022). This plant introduction and dispersal can anthropically occur when used in livestock activities as feed or naturally when water bodies carry plant fragments (FERREIRA *et al.* 2016; DIAMANTE *et al.* 2020). The accelerated growth of aquatic plants is related to the presence of nutrients, especially excess phosphorus, nitrogen, and potassium (CUNHA; ROCHA, 2014), and can negatively affect the natural behavior of water bodies.

In an attempt to ascertain which macronutrients *brachiaria* most requires, Bianco *et al.* (2015) conducted controlled experiments in a greenhouse, using pots with a sand substrate and irrigating them daily with a complete nutrient solution. The results show that the main macronutrients required by the plants were Potassium (K), followed by Nitrogen (N), Calcium (Ca), and Magnesium (Mg). Phosphorus (P) and Sulphur (S) had the lowest nutritional requirements.

Another factor that can limit the growth of *brachiaria* is the salinity level. The presence of this grass is uneven along the Guaraguaçu River: larger banks develop in areas of low salinity, while smaller banks occur in regions of high salinity (ARAÚJO; VITULE; PADIAL, 2021).

Studies conducted by Bora (2019) show that as salinity levels in the Guaraguaçu River increased, *brachiaria* growth and biomass decreased significantly. However, its survival can adapt to salinity conditions, and the permanence of this vegetation effectively occurs in regions where the maximum salinity values are 15.0 psu. From an ecological point of view, this can be explained as a survival strategy. Constant stress, in this case, caused by salinity, can develop the physiological tolerance of these plants due to acclimatization responses, *i.e.*, their high growth can occur as a way of reducing exposure to this stress (POTT *et al.* 2011; BORA; THOMAS; PADIAL, 2020).

## 2. Methodology

Defining hydrodynamic circulation is the initial step in studies of saltwater intrusion and the spreading of substances, and it also serves as the basis for further research. Considering the extreme complexity of transport mechanisms in estuaries and assuming that the transport of a given substance in a body of water is dominated by advection, this suggests a substantial dependence between the hydrodynamic simulation and the transport process.

Bahia's Environmental Hydrodynamics Base System (SisBaHiA<sup>®</sup>, Sistema Base Hidrodinâmico Ambiental) was used to calculate the hydrodynamics and transport processes of the Guaraguaçu estuary. SisBaHiA<sup>®</sup> uses finite elements for spatial discretization and finite differences for temporal discretization. The turbulent stress is parameterized according to filtering techniques based on Large Eddy Simulation (LES)<sup>1</sup>.

Three models were used in this study: the hydrodynamic model, used to solve the shallow water equations, using hydrostatic approximation for the pressure distribution and the Boussinesq approximation, in which the density is assumed to be constant except for the buoyancy terms (ROSMAN, 2021); the Eulerian transport model, used to analyze saltwater intrusion; and the Lagrangian particle dispersion model, forced with velocity fields from the hydrodynamic model, to simulate particle trajectories. In the present study, the hydrodynamic circulation in the Guaraguaçu River estuary is not detailed, but the reader can find more information on this subject in Sant'Ana (2023).

The Eulerian transport model uses an Eulerian approach for conservative parameters, which allows the analysis of salt concentration distributions for different river inputs to obtain the temporal evolution of saline intrusion at different intervals in the study domain. This transport model uses the same spatial grid as the hydrodynamic model and allows variable time step lengths in the analysis. The advantage of combining the two models appears when solving for velocities and turbulence coefficients, which was previously done in the hydrodynamic model and can be directly used in the transport model (ROSMAN, 2021).

The Lagrangian transport model is used to determine the spread of brachiaria in different fluvio-metric scenarios. This model enables the simulation of the transport of floating debris and the drift tendency of dissolved or particulate substances floating in natural bodies of water. In the Lagrangian model, the brachiaria bank is represented by a cloud with countless particles, advected by currents previously calculated using the hydrodynamic model. The main issue is obtaining the trajectory of these particles in the different regions of the estuary. From this model, it is also possible to indicate the areas of stagnation in the GRE using the results of the Lagrangian transport model.

The Lagrangian particle transport model has two boundary conditions. When a particle crosses a contour segment in open contours, it leaves the modeled domain and is removed. The second scenario occurs along soil contours. Two situations can occur along these boundaries: zero absorption, when the particle reaches the boundary and returns to the medium without any mass reduction, and partial or total absorption, when the particle returns to the medium but has a fraction of its mass (partial or total) absorbed along the reached boundary. The absorbed fraction is given by the absorption coefficient along the soil boundaries.

Salinity variations in the estuary were calculated using an Eulerian transport model. This model simulates the advective-diffusive transport of dissolved scalars in the water mass for different fluvio-metric scenarios, considering that river discharges influence hydrodynamic circulation and saline transport in the estuary.

The daily flows were obtained using the Soil and Water Assessment Tool (SWAT) hydrological model, used as boundary conditions in the hydrodynamic circulation model (SANT'ANA, 2023). SWAT is a semi-distributed hydrological model that allows the calculation of flows at different locations along the drainage basin, thus making it possible to create scenarios where soil usage and occupation changes can occur. Further details on the flow calculation can also be found in Sant'Ana (2023).

## 2.1 About the data used in the simulations

Figure 1 shows the modeling-defined domain with a quadratic finite element mesh with 2.801 finite elements and 13.900 nodes. The mesh is used to discretize the domain, locate the main rivers, and determine the longitudinal profile of the bottom elevation concerning mean sea level. The friction coefficient is defined in terms of the Chézy coefficient, which depends on the roughness amplitude of the bottom equivalent ( $\xi$ ). In the Guaraguaçu estuary, sand is predominant in the main channel ( $\xi$  equals 0.030 m).

The longest rivers in the hydrographic basin are the Guaraguaçu, approximately 43.0 km long, followed by the Cambará and Pery rivers, 22.0 km and 17.5 km long, respectively. The hydrography configuration shows that the

<sup>1</sup> For more information on the model and equations, refer to Rosman (2021) and the SisBaHiA<sup>®</sup> software website ([SisBaHiA - Sistema Base de Hidrodinâmica Ambiental \(ufrj.br\)](http://SisBaHiA - Sistema Base de Hidrodinâmica Ambiental (ufrj.br)))

Cambará and Guaraguaçu rivers have more tributaries. The Cambará River is a tributary of the Guaraguaçu River, and the Pery River is in the former's confluence region. The Pery River is vital to the area and has the worst water quality indices (ELSTE *et al.* 2019), as it is the primary recipient of urban drainage systems in the municipality of Pontal do Paraná. In the summer, there is a high influx of tourists because it is part of a coastal region with many leisure attractions. It causes a significant population increase and favors environmental imbalance in the area.

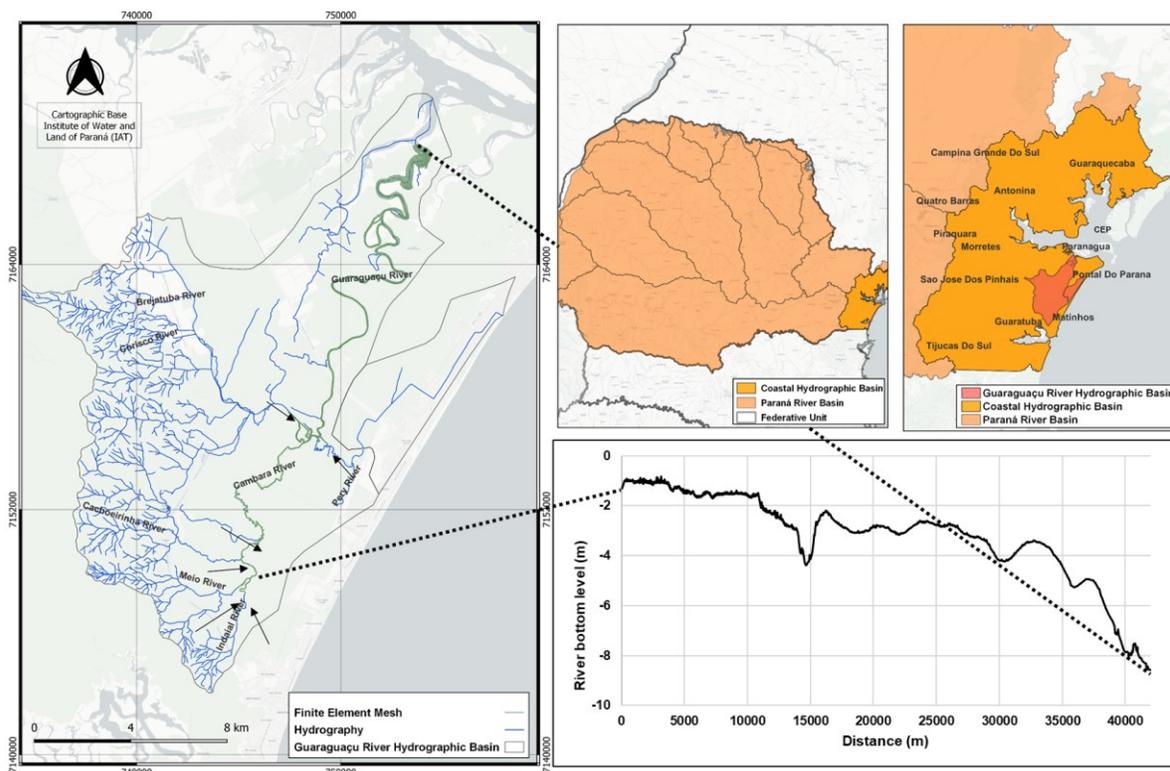


Figure 1 – Modeling domain, tributaries, finite element mesh, and longitudinal profile of the bottom elevation values concernin the mean level for the Guaraguaçu River.

Source: Authors (2024).

Two simulations were conducted to investigate the influence of the different river inputs on circulation and transport: the first, between 02/01/2020 and 02/28/2020, with rainy season river flow values, and the second, using dry season river flow data, observed between 07/01/2022 and 07/31/2022 (SANT'ANA, 2023). Figure 2 shows the flows considered in both season scenarios. In the rainy scenario, the most significant flow occurred on 02/08/2020, reaching approximately  $60.0 \text{ m}^3/\text{s}$  in the Guaraguaçu River. After the peak flow on 02/10/2020, an irregular rainfall distribution happened over this period, demonstrating a downward trend in flow values towards the end of the analysis.

On the other hand, in the dry scenario, the most significant flows were recorded at the series' beginning, specifically in the Guaraguaçu River, where they reached  $3.5 \text{ m}^3/\text{s}$ , followed by the Cambará and Pery rivers. These flows happened due to the rains that occurred before this period. It wasn't until 07/17/2022 that precipitation began again, resulting in a flow increase of the tributary rivers, with values close to  $3.0 \text{ m}^3/\text{s}$  in the Guaraguaçu River.

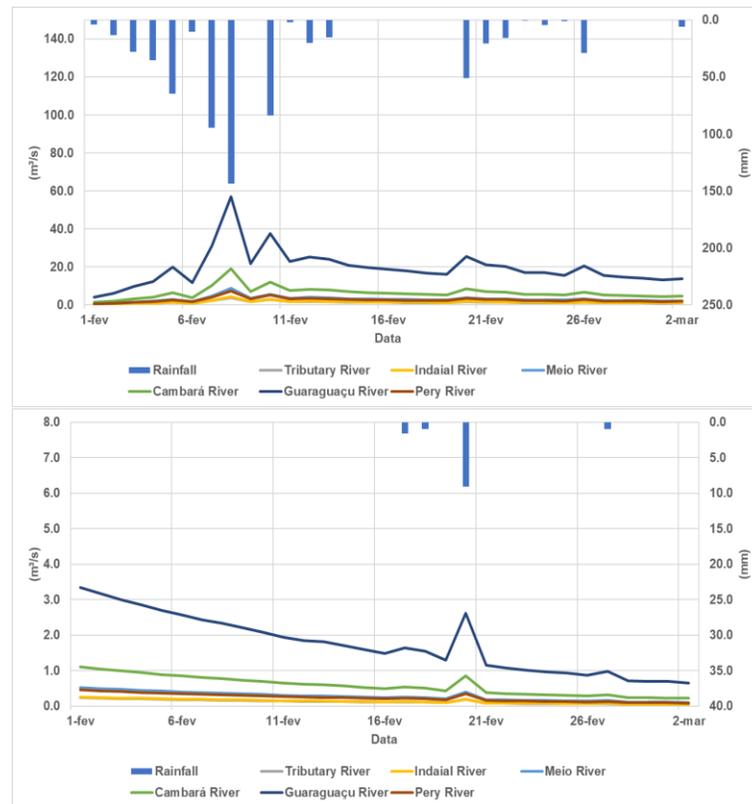


Figure 2 – Measured rainfall height and daily flow values in the rivers of the Guaraguaçu River basin for the rainy (above) and dry (below) scenarios obtained by SWAT.

Source: Authors (2024).

The tides govern the GRE hydrodynamic circulation with a semi-diurnal tidal regime and a maximum 2.0 m amplitude. When simulating hydrodynamic circulation, it is necessary to establish boundary conditions for the velocity field and the free surface elevation. The imposition of such an elevation is prescribed along the open contours, representing the limits of the domain, i.e., the estuary entrance. The flow imposition is usually associated with soil contours, rivers, or canals included in the modeling domain. The time interval used to simulate the hydrodynamic circulation was 5.0 seconds, corresponding to an average Courant number of 8.0. The Guaraguaçu estuary model had a warm-up period of two tidal cycles to minimize any influence from the initial conditions.

The brachiaria spreading was assessed based on the spatial distribution of the particles for the different periods, using the Lagrangian transport model from SisBaHiA<sup>®</sup>. Two brachiaria banks were selected for temporal evolution analysis: the first located in the freshwater dominance region (bank 1) and the second at the beginning of the estuarine region (bank 2). The aim is to describe the increase in brachiaria banks along the river. The location of the selected banks was obtained from studies conducted by Bora, Thomas, Padiál (2020). Figure 3 shows the location of the brachiaria banks chosen for 2009, 2019, 2021, and 2022. In 2009, the banks had smaller proportions than in 2022. Bank 1 was used as the source region, and the brachiaria spreading was simulated for 30 days. Figure 4 shows the initial position of the particles in bank 1. A total of 1,024 particles were released, distributed on a 1.0 m x 1.0 m grid.

The modeling of salt transport in the GRE was developed for the same periods of hydrodynamic circulation. Salinity values are prescribed along the open boundary and in the event of an inflow. In the dry scenario, salinity values vary between 15.0 and 21.0 psu at different time intervals of the spring and neap tides, following the free surface elevation oscillations. In the rainy season scenario, salinity was close to 16.0 psu at the start of the period, gradually decreasing in the next period. During the spring period, the values were between 13.0 and 7.0 psu, with increased oscillation (SANT'ANA, 2023). Figure 5 shows the saline concentration values used as a boundary condition (Station A). In the rivers, salinity was considered null.

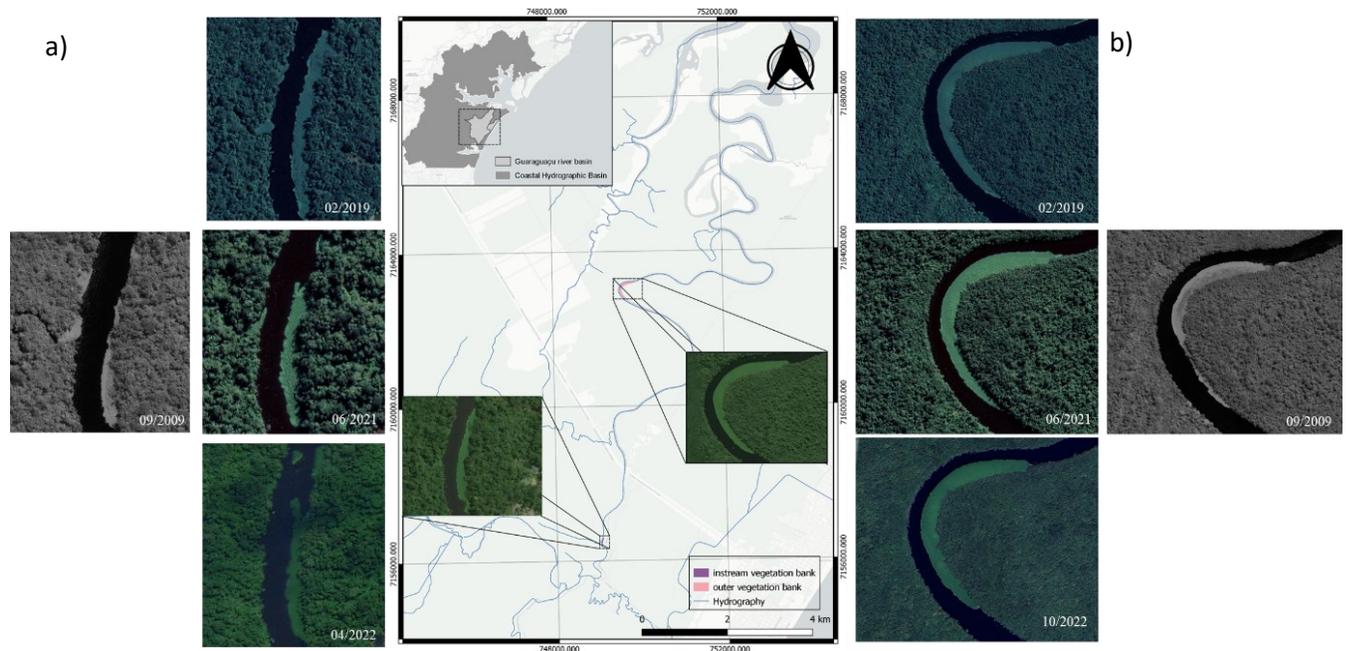


Figure 3 – Location of the brachiaria banks selected for the study in different years (2009, 2019, 2021, and 2023): (a) bank 1, in the freshwater dominance region; and (b) bank 2, the beginning of the estuarine region. Source: Authors (2024).

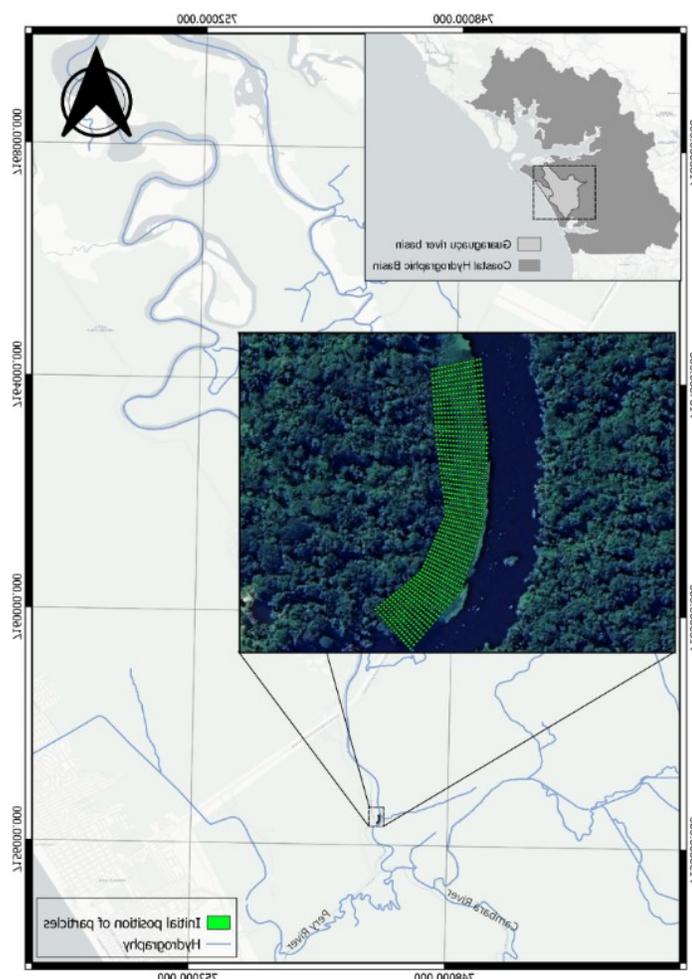


Figure 4 – *Brachiaria* bank location selected in the simulation and the initial position of the particles in the Lagrangian transport modeling.  
Source: Authors (2024).

### 3. Results

The results of the saline concentration are shown at four stations (Figure 5), representing different areas of the estuary: station D, the tidal zone of the river, with low salinity; station C, an intermediate area with a high compound of river and sea water; station B, the lower estuary region where there is great sea influence and; station A, near the mouth of the estuary, without fluvial input influence and under the strong influence of the PEC.

The results show that salt moves easily in the channels and how variations in river flow affect its distribution in the estuary. Figure 5 illustrates the variations in saline concentration over the two simulated periods. In the dry season, with reduced river flow, it can be seen that salinity oscillates with the tides, with stations A, B, and C showing similar behavior. At station A, salinity values are around 20.0 psu. At station D, salinity values are null until 07/25/2022, when there is a slight oscillation; on 07/30/2022, salinity values increase, exceeding the 0.5 psu limits, making the environment brackish. In the rainy season, salinity decreases, reaching null values at stations B, C, and D, approaching the boundary condition imposed by the rivers. At the end of the rainy season, salinity increases when flows decrease, particularly rapidly in the station B region. During both seasons, the tidal river zone (station D) has significantly low salinity due to the influx of fresh water from the rivers.

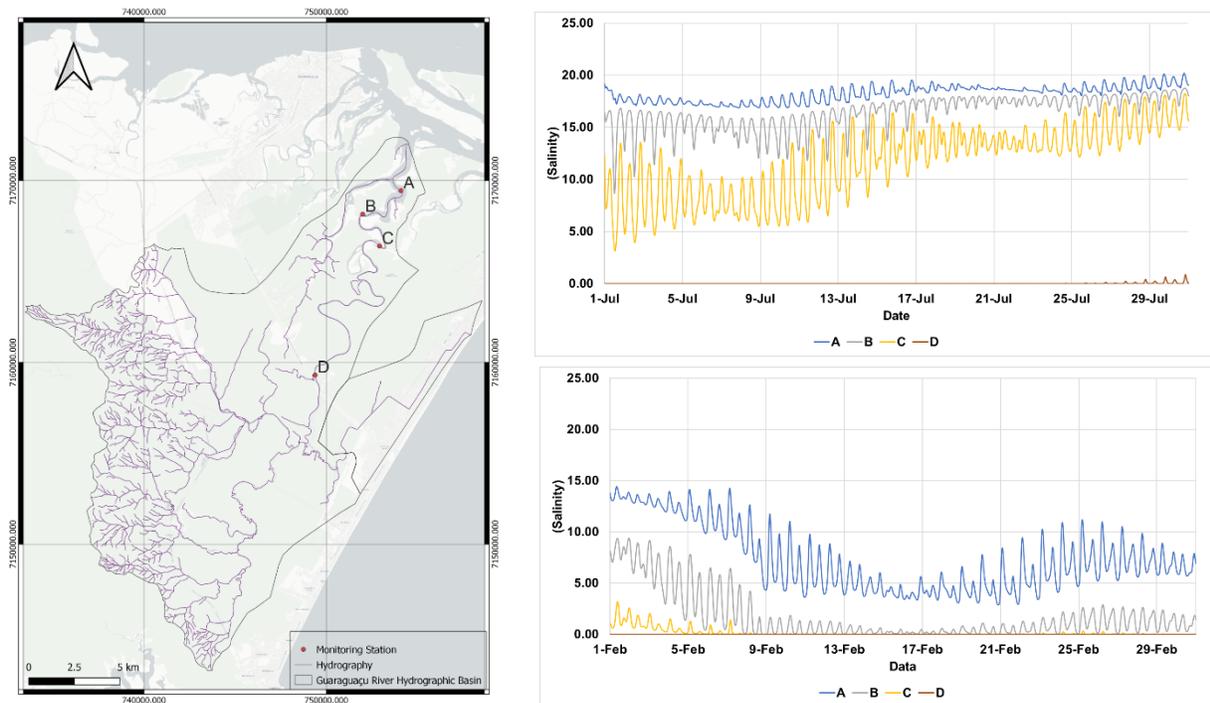


Figure 5 – Location of stations A (open border), B, C, and D where salinity concentration values (psu) were numerically obtained by SisBAHIA® for the dry (top) and rainy (bottom) seasons.  
Source: Authors (2024).

One of the results obtained from the model is the isoline map of salinity occurrences above 15.0 psu (Figure 6). In the rainy scenario, the Guaraguaçu River exhibits salinity levels below 15.0 psu throughout nearly the entire domain during the simulation, with values below 10‰ in the whole domain of the mouth region. On the other hand, in the dry scenario, salinity values exceeding 15.0 psu extend approximately 8.0 km from the mouth, indicating a larger area with levels above 15.0 psu during the dry season, with variations reaching up to the middle region.

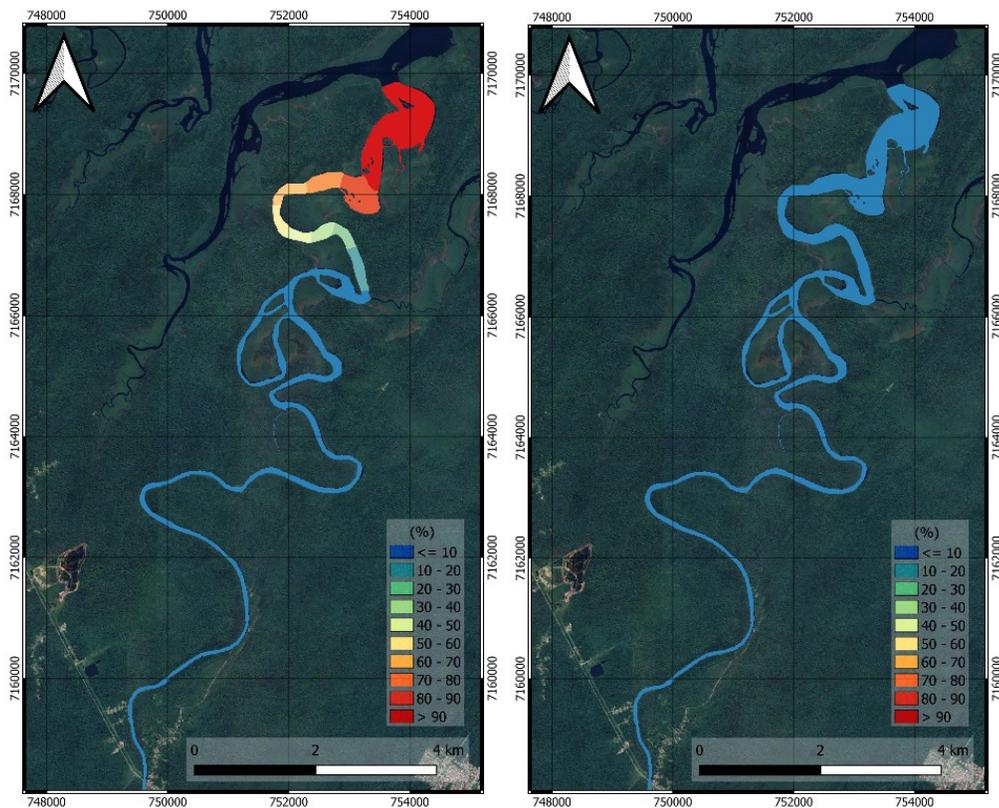


Figure 6 – Isoline map of salinity occurrence above 15.0 psu after 30 days during the dry season (left) and rainy season (right).

Source: Authors (2024).

Figure 7 presents the results of brachiaria spreading after 2, 16, and 30 days from the start of the simulation during the dry season, considering the scenario where particles are reflected upon reaching the margins. It can be observed that the particles remain within the Guaraguaçu River and do not reach the mouth of the estuary even after 30 days. If the particles are completely absorbed upon reaching the margins (Figure 7), they will quickly be trapped in the more sinuous parts of the river—approximately one day after the start of the simulation—and will not reach the estuarine region. In both simulations, the particles migrate toward the mouth, showing the dynamics of brachiaria spreading.

The results of the rainy season (Figure 8) show that after the particles reach the shore and are reflected, they take 8 days to reach the estuarine region. The particles leave the domain entirely after 25 days from the start of the simulation. Therefore, the brachiaria can migrate to the PEC when the river input is higher. When total absorption is considered (Figure 8), the results also show that the brachiaria are contained in the sinuous region of the Guaraguaçu River. This is possibly associated with higher velocities in the Guaraguaçu River during the rainy season, causing greater dispersion of the particles.

### 3.1 Discussion

The results show that the fluvial input is the main hydrodynamic forcing in the Guaraguaçu estuary. The river's narrow channels dampen the tidal wave, making it a secondary factor in the hydrodynamics of the estuary. The simulations demonstrate that dissolved substances, represented by inert particles, tend to move towards the river mouth more easily during the rainy season and can leave the estuary in the direction of the PEC. During the dry season, the particles remain within the estuary for the entire period, indicating a higher probability of fixation in the inner regions of the Guaraguaçu River.

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Considering the margins' absorption capacity, it is possible to understand how the brachiaria behave for different absorption levels. For a boundary with total absorption, which represents the situation closest to reality and takes into account the characteristics of the banks of the Guaraguaçu River, it was possible to observe the brachiaria fixating in the most sinuous regions of the river, corroborating the landscape described in Bora, Thomas, Padiál (2020).

Salinity plays a fundamental role in the survival of brachiaria. According to the results of Bora (2019), salinity levels below 15.0 psu favor the permanence of brachiaria in regions. The results show that during the rainy season, the Guaraguaçu River has a salinity of less than 15.0 psu along practically its entire length; in the mouth region, it is above 15.0 psu for only 5% of the simulation time. On the other hand, approximately 8.0 km from the mouth, salinity values are higher than 15.0 psu during the dry season.

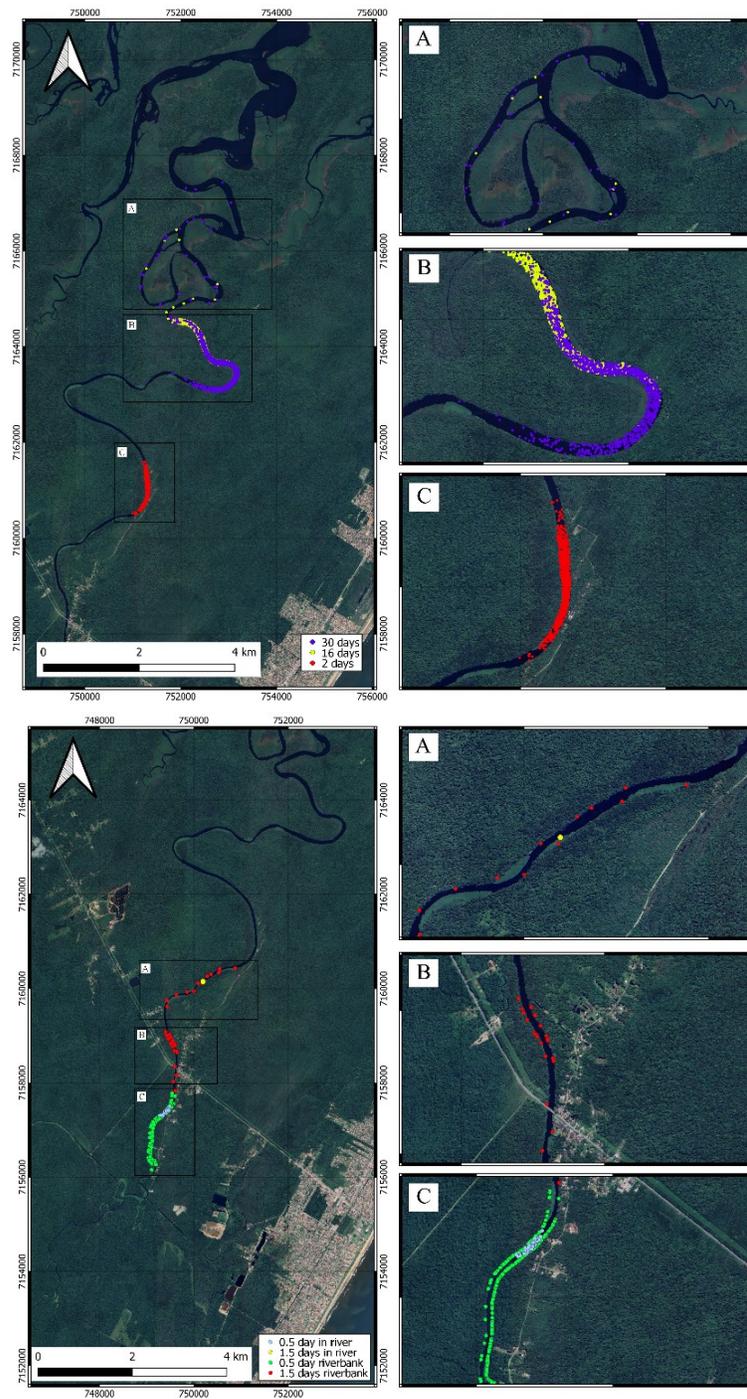


Figure 7 – Distribution of particles after 2, 16, and 30 days in the dry season with null absorption (above) and after 0.5 and 1.5 days in the dry season with total absorption (below).  
Source: Authors (2024).

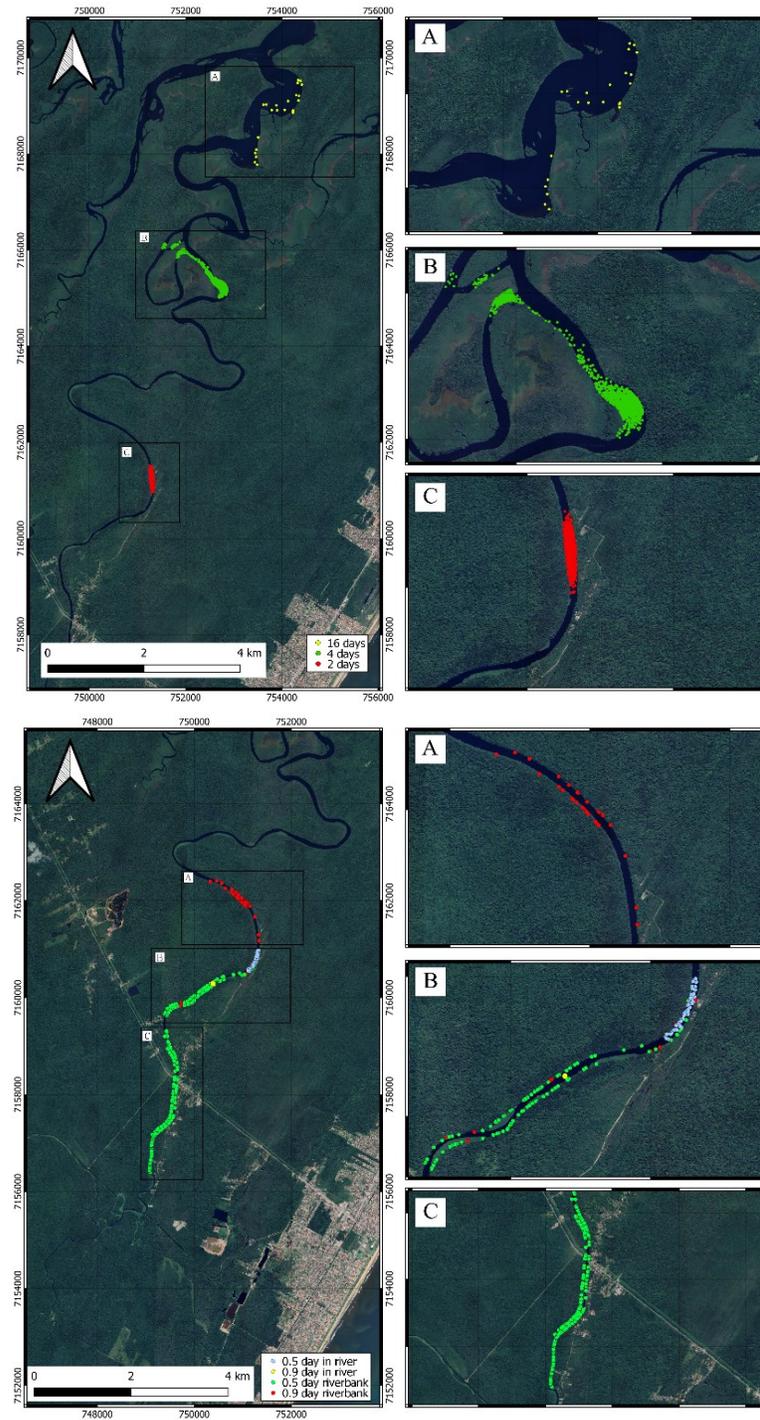


Figure 8 – Distribution of particles after 2, 4, and 16 days in the rainy season with null absorption (above) and after 0.5 and 1.5 days in the rainy season with total absorption (below).  
 Source: Authors (2024).

In the dry season, even with higher salinity values, brachiaria permanence is possible, as they can fixate on the margins. On the other hand, during the rainy season, the brachiaria are more likely to leave the estuary, but the low

salinity may make it easier for them to fixate. It enables the species' adaptation to dry seasons, where the inner regions of the river's higher salinity conditions do not prevent its permanence, while the rainy season can facilitate its transport to more remote areas. It can be concluded that during the rainy season, the brachiaria spreads into the Guaraguaçu River, reaching its mouth and having its fixation facilitated by the low salinity.

Regarding possible areas of stagnation in the estuary that could facilitate the fixation of brachiaria, the results indicate that the grass tends to settle in the more sinuous river regions, where water velocity is lower. During high-flow periods, some brachiaria remain in the river beds, and others leave the estuary.

It is important to note that brachiaria need nutrients to ensure their survival and reproduction. Reducing the nutrient load reaching the system, mainly through the Pery River, would be a preventive measure to control the expansion of brachiaria in the Guaraguaçu River. Other corrective measures, such as mechanical removal or the use of herbicides, are less efficient and particularly impactful, as the river is part of an environmental preservation area, and the use of herbicides can be detrimental to the ecosystem health and the riverside communities.

#### 4. Conclusions

In estuarine environments, saline concentration limits the spread and dispersal of brachiaria, while their growth is accelerated when nutrients are abundant. River inflow and the species' fixation capacity influence these parameters. This study demonstrates that the spreading and dispersion of brachiaria vary under different scenarios of water input (dry and rainy) and fixation (total and null absorption).

The results show that the particles used to describe the brachiaria move more easily to the mouth of the river during the rainy season and, therefore, have the potential to reach areas outside the estuary. In contrast, the particles remain within the estuary during the dry season, indicating a high fixation probability in the inner regions. It highlights how brachiaria spread in the Guaraguaçu River estuary under different fluviometric scenarios.

This work also reveals that variations in salinity levels influence their fixation. In the rainy season, at the mouth of the estuary, salinity is low, with values below 15.0 psu, and the brachiaria can reach the region, which probably favors their fixation during this period. During the dry season, salinity increases at the mouth of the river, which can prevent brachiaria from surviving in the area. However, the species may have adapted to high salinity conditions.

Regarding the areas of stagnation in the Guaraguaçu River estuary and their influence, from the spreading of the brachiaria until it fixates, it is observed that with null absorption, particles remain within the estuary during the dry season. In contrast, during the rainy season, the particles quickly reach the mouth of the river and leave the domain entirely after 25 days, potentially reaching the Paranaguá Estuarine Complex. With total absorption, particles tend to settle on the river margins in both periods, remaining stagnant in the more sinuous regions.

#### Acknowledgments

The authors would like to thank the Academic Publishing Advisory Center (Centro de Assessoria de Publicação Acadêmica, CAPA – <http://www.capa.ufpr.br>) of the Federal University of Paraná (UFPR) for assistance with English language translation and developmental editing.

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