

Article

How to Manage Invasive *Hovenia dulcis* Trees in Native Forests? A Case Study on Rural Properties in South Brazil

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Abstract

Sustainable management of the invasive tree *Hovenia dulcis* (*H. dulcis*) in the Mixed Om-brophilous Forest (MOF) is crucial for reconciling biodiversity conservation with income generation for smallholders. This study developed a species-specific predictive growth model for *H. dulcis* and simulated management scenarios across three properties with contrasting invasion intensities. By integrating stem quality, phytosanitary status, and individual growth rates into tree selection criteria, we evaluated trade-offs between timber yield and structural recovery under Continuous Cover Forestry (CCF) principles. The mixed-effects growth model demonstrated high predictive performance (marginal $R^2 = 0.89$, RMSE = 2.05 cm), confirming H1 and validating its application as a decision-support tool for long-term silvicultural planning. Results confirmed H2: no single standardized management approach proved appropriate across all sites, as invasion intensity, stand density, and diameter distribution varied substantially among properties and directly determined the most suitable harvesting strategy. In highly invaded stands (Property I), intensive harvesting of 61 trees yielded the highest commercial volume ($V_c = 21.84 \text{ m}^3$), while in more preserved forests (Property II), conservative selection of 26 trees ($V_c = 9.53 \text{ m}^3$) prioritized structural quality. Structural recovery periods ranged from 1 to 7 years depending on harvesting intensity, with removal of stagnant large-diameter trees reducing passage time for remaining individuals. Targeting sawlog-quality trees ($\text{dbh} > 25 \text{ cm}$) was 3.35 times more profitable than firewood production, providing a significant economic incentive for smallholders. These findings demonstrate that property-specific *H. dulcis* management can transform a biological threat into a productive resource, fostering MOF restoration through active and sustainable use.

Keywords: invasive species; forest management; small properties; *Hovenia dulcis*; native forests

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1. Introduction

Biological invasions are increasingly recognized as one of the major threats to global biodiversity, causing profound changes in ecosystem structure, species composition, and ecological processes [1]. In forest ecosystems, invasive alien species can suppress native regeneration through competition for light, water, and nutrients, alter vertical forest structure, modify species composition, and contribute to the long-term homogenization of forest communities [1,2]. Invasive tree species in particular decrease ecosystem resilience with negative impacts on natural regeneration, reducing taxonomic, functional, and phylogenetic diversity of native tree species in invaded stands. These impacts are especially severe in fragmented and historically disturbed forest remnants, where reduced biotic resistance and altered light regimes facilitate the establishment and expansion of invasive populations.

The Mixed Ombrophilous Forest (MOF), commonly known as the Araucaria Forest, represents one of the most ecologically significant and threatened forest formations of the Atlantic Forest biome in southern Brazil. Characterized by the emblematic *Araucaria angustifolia* (Brazilian pine), the MOF has been drastically reduced and fragmented over past decades due to intense timber exploitation and agricultural expansion, with only a small proportion of primary remnants remaining in protected areas and isolated patches on private rural properties [3,4]. Such fragmentation-driven vulnerability facilitates the establishment of invasive species that alter forest structures, compete with native flora, and compromise regeneration processes, posing an additional challenge for conservation and sustainable management of the MOF.

Among the invasive species threatening MOF remnants, *Hovenia dulcis* Thunb. (Japanese raisin tree) stands out as one of the most ecologically disruptive. Native to East Asia—China, Japan, Korea, Thailand, and Vietnam—*H. dulcis* is a fast-growing, shade-tolerant deciduous tree reaching 20–30 m in height, reproducing sexually by seeds, and preferring sunny positions on well-drained, moist soils. Introduced in Brazil for ornamental and timber purposes [5], the species produces fleshy, sweet peduncles that facilitate zoochorous seed dispersal, contributing to its high colonization capacity. Studies in the MOF have recorded densities of up to 334.5 plants per hectare in restoration areas and a mean of 911 young individuals per hectare in forest fragments, with higher invasion capacity in areas at early and intermediate stages of secondary succession. *H. dulcis* is considered the main invasive species in the Atlantic Forest, capable of altering environmental conditions at a local scale and producing profound changes in the composition of the plant community. By forming dense adult populations with high canopy closure, the species generates substantial understory shading that suppresses the regeneration of light-demanding native species, particularly *Araucaria angustifolia* [6,7].

Brazilian environmental legislation, specifically the Forest Code (Federal Law 12,651/2012), requires rural properties to maintain a Legal Reserve of at least 20% of their total land area under native vegetation, where both the suppression of native species and land-use conversion are restricted [8]. This regulatory framework effectively limits the management options available to smallholders in MOF remnants, as sustainable harvesting of native timber species is subject to strict authorization processes that are often inaccessible to small rural producers [8,9]. In this context, the controlled management and productive use of *H. dulcis*, whose removal is not only legally permitted but ecologically recommended, represents a particularly strategic opportunity. Sustainable management of invasive species such as *H. dulcis* not only supports the regeneration of native species and the restoration of the MOF's natural structure, but can also generate additional income for farmers, transforming an ecological liability into a productive forest resource.

Despite the growing ecological and economic relevance of *H. dulcis* management in southern Brazil, existing studies on the species have focused primarily on aspects such as

invasion dynamics [10], species distribution modelling [2], and remote sensing detection [11], with no species-specific individual tree growth model currently available to support evidence-based management decisions across different invasion intensities and forest structures in the MOF. This knowledge gap limits the ability of managers and policymakers to design adaptive, site-specific interventions that simultaneously balance ecological restoration with income generation for smallholders.

In this study, we aimed to develop a management approach for *H. dulcis* in native MOF forests that simultaneously promotes conservation and income generation through sustainable forest management strategies. Specifically, we sought to (i) develop a species-specific growth model for *H. dulcis* based on individual tree attributes; (ii) evaluate whether a standardized management framework can be applied across different farm contexts with varying invasion intensities; and (iii) identify the most appropriate management strategies for each property to support sustainable management while providing economic benefits to landowners. We hypothesized that (H1) a species-specific linear mixed-effects growth model integrating individual tree attributes can provide reliable estimates of future diameter growth for *H. dulcis* across properties with contrasting stand structures, and (H2) that invasion intensity, stand density, and tree size distribution vary sufficiently among sites to require property-specific, rather than standardized, management strategies.

2. Methods

2.1. Study Area

The data utilized in this study originates from three private properties located in the municipality of Fernandes Pinheiro, Paraná state, Brazil (Figure 1). These properties are part of the project titled “Strategies for Sustainable Forest Management in Small Rural Properties in the Central-South of Paraná,” known as the “Projeto Imbituvão.”

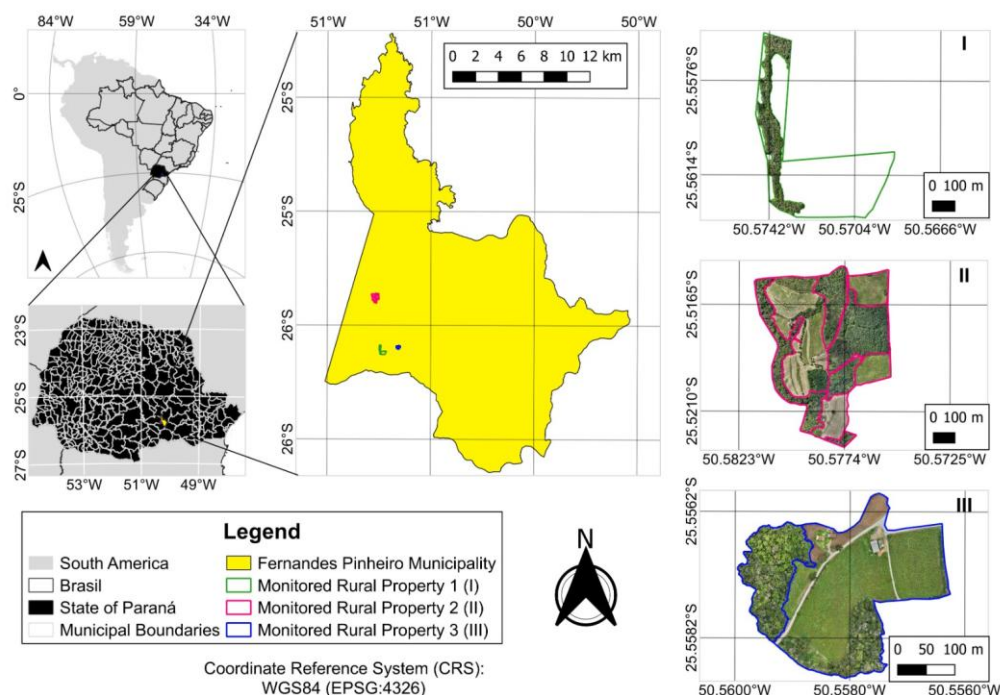


Figure 1. Localization of the study area.

2.2. Data Collection

2.2.1. Census of *Hovenia dulcis*

To obtain the necessary information for diagnosing the invasion process and planning the management of *H. dulcis*, a complete inventory of the species (census) was conducted in 2018, following the methodology established by [6].

The census adopted a minimum diameter of 10 cm for inclusion. All *H. dulcis* trees were numbered and georeferenced using the Global Positioning System (GPS). Numbering was done according to each rural property, meaning each property had its own numerical sequence of individuals. The variables measured in the census included:

- (a) Diameter at 1.30 m from the ground (dbh): Measured with a standard measuring tape. The measurement point was marked with blue paint to facilitate future measurements, and the tree number was also painted above this point.
- (b) Commercial height (hc): Defined as the height from the ground to the first branch coinciding with the start of the crown, measured with a graduated pole.
- (c) Stem quality class.

The individuals were visually graded based on their suitability for sawmilling, following the methodology adapted from [7]:

- (1) Straight stem: The trunk is straight, cylindrical, and free of significant defects, making it ideal for high-value timber products (sawlogs).
 - (2) Slightly twisted stem: The trunk shows minor deviations or slight curvature but still maintains a minimum commercial length for secondary timber products.
 - (3) Twisted stem: The trunk exhibits severe tortuosity, bifurcations at low heights, or excessive branching, being unsuitable for sawmills and restricted to firewood or energy production.
- (d) Vertical stratification class

Each tree was categorized according to its position in the forest canopy to assess its ecological dominance and light access:

- (1) Upper stratum (Dominant): Trees whose crowns receive full light from above and partially from the sides, forming the main canopy layer.
 - (2) Middle stratum (Intermediate): Trees that receive direct light from above but little to no light from the sides, being partially shaded by the upper stratum.
 - (3) Lower stratum (Suppressed): Trees located entirely beneath the canopy, receiving only diffuse light. These individuals often show stagnant growth due to high competition.
- (e) Phytosanitary class

The health status of each tree was evaluated based on visible external indicators:

- (1) Good health: The individual is vigorous, with a dense crown and a stem free of visible damage, fungi, or galleries.
 - (2) Average health: Trees showing minor signs of decline, such as partial loss of foliage, presence of epiphytes, or small mechanical scars on the bark.
 - (3) Poor health: Individuals severely compromised by pests, stem rot, hollows, or significant crown dieback. These trees were prioritized for removal in scenarios focused on forest sanitation and quality improvement.
- (f) Extraction difficulty class:
- (1) Easy extraction: Trees located in areas with easy access for extraction equipment and forest winches, typically on flat or gently sloping terrain.
 - (2) Moderate extraction difficulty: Equipment access is more challenging, with terrain having moderate to steep slopes.

- (3) Difficult extraction. Extreme difficulty for equipment access and extraction, with terrain featuring severe slopes.

(g) Quality class

This classification determines the final commercial destination of the timber, integrating the parameters of stem quality, phytosanitary status, and dimensions.

- (1) Timber quality (Sawlogs): This class includes individuals with a straight stem (Quality 1 or 2), good phytosanitary status (Health 1), and a minimum Diameter at Breast Height (dbh) suitable for industrial processing (typically > 18–20 cm) [6].
- (2) Energy use (Firewood/Biomass): This class comprises individuals that do not meet the requirements for sawmilling due to severe stem tortuosity (Quality 3), poor health (Health 3—e.g., rot or hollows), or reduced dimensions.

Crown areas of a subset of trees were measured following the methodology described by [12]. For each tree in the subset, the crown area was determined by measuring four radii in cross-sections, assuming an elliptical or circular projection. To estimate the crown area for the remaining unmeasured individuals, a second-order polynomial model was fitted using Diameter at Breast Height (dbh) as the independent variable:

$$\text{CrownArea}_i = \beta_0 + \beta_1 \text{dbh}_i + \beta_2 \text{dbh}_i^2$$

where dbh_i is the final stem diameter of tree i . Estimated crown areas were subsequently included as a predictor in the tree growth models to improve representation of individual structural variability.

Three properties were selected for management and their characteristics are described in Table 1.

Table 1. Description of selected properties.

Property/Local	Area (ha)	Total of <i>H. dulcis</i> Trees per Site	Volume (m ³) (per Site)
I	4.04	210	44.97
II	6.85	210	33.92
III	2.27	168	34.36

2.2.2. Growth Model

A mixed linear model to estimate tree growth was developed, incorporating both fixed and random effects to account for variability in the data. To model the future diameter at breast height (dbh_t) of *H. dulcis*, we fitted the model using a dataset of 447 trees measured across the three forest properties. Mixed models were selected to separate the deterministic component of tree growth (fixed effects) from variability associated with measurement periods and spatial heterogeneity across forest locations (random effects) [13,14].

Specifically, the fixed-effects structure was defined to include the key tree-level predictors known to influence diameter growth: dbh in the present: current diameter at breast height (cm), hc: commercial height (m), crown: crown projection area (m²) and period: number of years between consecutive measurements. These predictors have been widely reported as key drivers of individual tree diameter growth in uneven-aged forests [15–17]. These predictors represent the expected, systematic effect of tree size and morphology on future growth, allowing the model to capture underlying biological processes governing diameter increment. Two sources of random variation were incorporated: Forest location and measurement period (plot × year effect).

These were represented in the model as a random intercept term:

$$b_{0j}$$

where $j = 1, 2, 3$, allowing each property to have its own baseline growth level.

The period between measurements was modeled as a random effect to account for temporal variability not fully explained by the fixed predictor *period*. This captures inter-annual fluctuations potentially caused by climate, forest condition, or measurement inconsistencies. Thus, the model includes random intercepts for both locality and measurement period.

2.3. Mathematical Model Structure

Let:

i = tree;

j = locality (forest property);

k = measurement period.

The mixed model is expressed as:

$$dbhf_{ijk} = \beta_0 + \beta_1 dbhp_{ijk} + \beta_2 hc_{ijk} + \beta_3 crow_{ijk} + \beta_4 period_{ijk} + b_{0j} + c_{0k} + \varepsilon_{ijk}$$

where $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$ are the fixed-effect parameters to be estimated.

2.3.1. Random Effects

$b_{0j} \sim N(0, \sigma_{locality}^2)$: random intercept for locality;

$c_{0k} \sim N(0, \sigma_{period}^2)$: random intercept for measurement period;

$\varepsilon_{ijk} \sim N(0, \sigma^2)$: residual error.

For diameter projection over short to medium periods, we consider the commercial height of the tree to be constant. Significant variation in commercial height typically occurs over longer periods. Therefore, there is no need for a height growth model in this context.

We utilize growth models to simulate the long-term effects of each scenario on forest dynamics and the *Hovenia dulcis* population.

2.3.2. Model Validation and Performance Assessment

Model performance was evaluated using root mean square error (RMSE), mean absolute error (MAE), bias, and coefficient of determination (R^2). Predictions were generated using fixed effects only to assess population-level predictive ability. Validation was conducted using both independent training-test partitioning (70/30 split) and k-fold cross-validation ($k = 5$) [18].

Residual diagnostics were examined visually using residual vs. fitted plots and quantile–quantile plots to assess homoscedasticity and normality assumptions.

Variance components were extracted to quantify the relative contribution of random effects to total variance. Marginal and conditional R^2 values were calculated to distinguish variance explained by fixed effects alone versus the full mixed model [19].

2.4. Scenarios

2.4.1. Cutting Rate

Ingrowth, mortality, and harvest rate of *H. dulcis* were assessed using data from permanent plots over three distinct periods: 2011–2014, 2014–2017, and 2017–2022. These intervals were selected to align with the long-term monitoring cycles of the regional forest inventory, ensuring a comprehensive 11-year dataset that accounts for temporal variations in demographic rates. The rates were calculated as the percentage of trees that entered or died in relation to the initial number of trees in each period. Subsequently, the average rate between the measurement periods was calculated for the same variables (in-

growth, mortality and harvest rate). The average ingrowth rate between the three periods was used as the basis for determining the cutting intensity in management planning. All trees that reached the 10 cm dbh inclusion threshold during the evaluation period were counted as ingrowth [6,7].

2.4.2. Scenario Description

The management scenarios were designed to prioritize the transition from an invaded stand to a productive, high-quality forest structure under Continuous Cover Forestry (CCF) principles. The following criteria were applied:

Silvicultural Selection: Trees with lower stem quality (Class 3) and poor phytosanitary status (Health 3) were prioritized for removal. This “sanitation cutting” aims to release growing space, reduce competition for light, and decrease the “passage time” for high-quality remaining individuals [6,7].

Diameter Class Distribution: Harvesting was distributed across all diameter classes to maintain a balanced forest structure. However, specific focus was given to individuals with stagnant growth in both lower and upper strata to stimulate the recruitment of native species and vigorous *H. dulcis* individuals.

The scenarios and their specific objectives are detailed in Table 2. The cutting intensity was calibrated based on the average ingrowth rate of the species (approx. 5% of stems), resulting in the removal of 33 trees from Property I, 15 trees from Property II, and 26 trees from Property III.

Table 2. Description of the scenarios and sub-scenarios and their objectives for tree selection.

Scenario	Aim	Subscenario	Aim
1	Select trees with dbh exceeding 25 cm	1.1	Select trees with dbh > 25 cm up to the prescribed cutting rate, based on the average ingrowth rate.
		1.2	Remove all trees with dbh > 25 cm
2	Selecting trees with poor health and low stem quality	2.1	Remove all trees with dbh > 25 cm and low stem quality
		2.2	Remove trees with dbh > 25 cm combined with trees of poor health and low stem quality
3	Select trees with stagnant growth rate	3.1	Remove trees with growth rate below 1.5% over a 4-year period
		3.2	Remove trees with dbh > 25 cm and growth rate below 1.5% over a 4-year period
4	Balanced structure following Meyer’s method [20]	4.1	Remove trees with dbh > 25 cm according to the balanced diameter distribution
		4.2	Remove trees across all diameter classes; trees below 25 cm selected by stem quality and health

2.4.3. Property-Specific Adaptations

The application of scenarios was tailored to the unique forest structure of each site: Property III: Sub-scenario 1.2 was not applied because the frequency of trees exceeding 25 cm dbh was lower than the prescribed cutting rate; these individuals were instead integrated into sub-scenario 1.1. Similarly, sub-scenario 2.2 was omitted as the density of trees below 25 cm dbh was insufficient, with its objectives effectively covered by sub-scenario 2.1.

Property I: Due to the “Very High Invasion Level” and superior tree density, an additional scenario (4.2) was feasible, allowing for a more intensive disruption of the invasive canopy to promote understory light availability.

3. Results

The 2022 census recorded a total of 210, 210, and 168 *Hovenia dulcis* individuals in Properties I, II, and III, respectively, all with dbh ≥ 10 cm. Descriptive statistics for all measured and classified variables are presented in Table 3. Property I showed the highest mean dbh (20.78 ± 7.10 cm) and the greatest proportion of straight-stemmed individuals (62.4%), indicating a more structurally advanced invasion with higher timber potential. Property II presented the lowest mean commercial height (5.81 ± 2.36 m) and the highest proportion of firewood-quality individuals (81.3%), suggesting a stand dominated by lower-quality stems despite a similar stem density to Property I. Property III was characterized by the tallest individuals on average (8.94 ± 2.36 m) and the highest proportion of twisted stems (17.3%), reflecting a distinct structural profile from the other two sites. Phytosanitary status was generally good across all properties, with poor health recorded in less than 4% of individuals in any site. Extraction difficulty varied substantially among properties, with Property I showing the highest proportion of moderately difficult extraction (52.5%), contrasting with Properties II and III where easy extraction predominated. These structural differences among properties provide the empirical basis for the property-specific management scenarios developed in this study and are further discussed in relation to the simulated harvesting outcomes.

Table 3. Descriptive characteristics of *Hovenia dulcis* individuals recorded across the three study properties during the 2022 census. dbh = diameter at breast height; SD = standard deviation.

Variable	Property I	Property II	Property III
General			
Total individuals (n)	210	210	168
Mean dbh $\pm$ SD (cm)	20.78 ± 7.10	18.72 ± 6.49	19.38 ± 5.49
Min–Max dbh (cm)	10.28–46.89	10.06–39.69	10.38–46.41
Mean commercial height $\pm$ SD (m)	6.83 ± 2.60	5.81 ± 2.36	8.94 ± 2.36
Total commercial volume (m ³)	44.97	33.92	34.36
Total volume (m ³)	67.22	52.27	44.16
Stem quality (%)			
Class 1—straight	62.4	39.5	32.1
Class 2—slightly twisted	31.4	51.0	50.6
Class 3—twisted	6.2	9.5	17.3
Vertical position (%)			
Class 1—upper stratum	62.4	51.4	63.1
Class 2—middle stratum	35.7	44.8	33.3
Class 3—lower stratum	1.9	3.8	3.6
Phytosanitary status (%)			
Class 1—good	94.7	90.5	95.8
Class 2—average	5.3	5.7	3.0
Class 3—poor	0.0	3.8	1.2
Extraction difficulty (%)			
Class 1—easy	45.1	64.3	63.1
Class 2—moderate	52.5	10.4	16.7
Class 3—difficult	2.5	25.3	20.2
Timber quality (%)			
Class 1—sawlogs	47.5	18.7	29.2
Class 2—firewood/biomass	52.0	81.3	70.8

The mixed-effects model demonstrated strong predictive performance for final tree diameter, with fixed effects explaining 89% of the variation in final diameter (marginal R^2), while including random effects increased the explained variance to 91% (conditional R^2), see Table 4. Prediction errors were low (RMSE = 2.05 cm, MAE = 1.51 cm) and bias was negligible, confirming accurate and unbiased predictions. Cross-validation showed slightly higher errors (RMSE = 2.27 ± 0.27 cm, MAE = 1.7 ± 0.13 cm), indicating good model generalization and stability.

The goodness-of-fit of the dbh growth model was also evaluated through residual analysis (Figure 2). The relationship between observed and predicted dbh values showed a strong linear correlation, with data points closely following the 1:1 line, indicating high predictive accuracy. The scatter plot of standardized residuals against predicted values revealed a random distribution around the zero line, suggesting homoscedasticity and no significant systematic bias across the range of tree sizes. Furthermore, the histogram and density plot of standardized residuals exhibited a near-normal distribution centered at zero, confirming that the model assumptions were met and that it provides a reliable fit for *H. dulcis* growth characteristics.

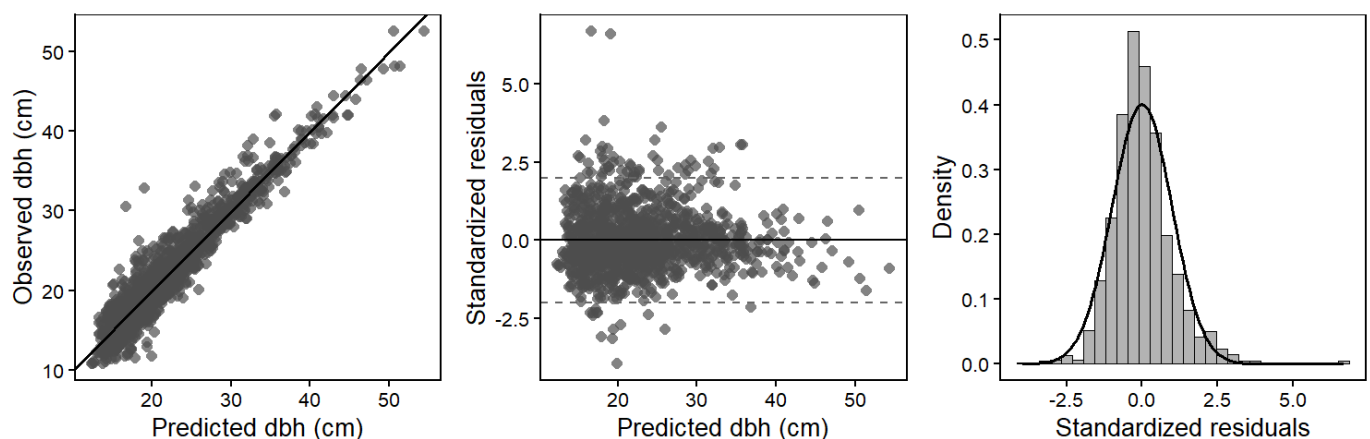


Figure 2. Model evaluation: observed versus predicted dbh values (solid line represents the 1:1 relationship), standardized residuals versus predicted dbh values (dashed lines indicate the ± 2 standardized residual limits), and distribution of standardized residuals (solid curve represents the kernel density estimate).

All fixed effects were highly significant ($p < 0.0001$), with diameter at previous measurement (dbhp) being the strongest predictor ($\beta = 0.919$), followed by period, crown area, and commercial height (hc), see Table 5. Variance component analysis revealed that strongest variability of random effects originates from residual (78.5%), followed by property (17.7%) and measurement period (3.8%), indicating that individual tree differences contribute substantially to growth variability. Overall, the model accurately captures both systematic effects of tree morphology and hierarchical variation among trees and measurement periods.

Table 4. Goodness of fit of the growth model for *H. dulcis*.

Metric	Model Fit	Cross-Validation (5-Fold)
RMSE (cm)	2.05	2.27 ± 0.27
MAE (cm)	1.51	1.7 ± 0.13
Bias (cm)	0	-0.11 ± 0.11
R^2 (marginal)	0.89	-
R^2 (conditional)	0.91	-

To evaluate forest dynamics post-intervention, we modeled the recovery of dbh classes and total volume alongside future tree frequency. As shown in Table 6 and Figures 3 and 4, these simulations compare different management strategies by quantifying timber extraction and the period necessary for the forest to return to its baseline structure.

In Property I, Scenario 3.2 achieved the highest harvest intensity, removing 61 trees characterized by large diameters and stagnant growth. This intervention yielded the maximum volume across all analyzed scenarios ($V_c = 21.84 \text{ m}^3$; $V_t = 34.74 \text{ m}^3$) with a projected recovery period of 5 years. This scenario was selected for its operational efficiency, offering a high volumetric yield while maintaining a viable harvesting interval that avoids excessive forest disturbance. This intervention not only maximized short-term economic return but also promoted structural renewal by reducing competition and resources for more vigorous individuals. Such selective removal of low-productivity dominant trees is widely recognized as a mechanism to stimulate stand growth and improve resource allocation in uneven-aged forests [21,22].

Table 5. Estimated parameters of the linear mixed-effects model.

Fixed Effects			
Parameter	Estimate	F-Value	p-Value
(Intercept)	2.654	71,641.42	<0.0001
dbhp	0.919	6410.74	<0.0001
hc	−0.143	354.29	<0.0001
Crown	0.045	62.28	<0.0001
Period	0.603	573.22	<0.0001
Random Effects			
Component	Var	sd	Var (%)
Property/local	0.965	0.982	17.72
Period	0.206	0.453	3.78
Residual	4.273	2.06	78.49

Var is variance; sd is standard deviation, Var (%) is the relative variance for each component.

Scenario 4.2 followed Meyer's balanced forest principle, requiring 4 years to restore the total stem density above 25 cm dbh and a 7-year cutting cycle for full restoration of the balanced diameter distribution. Scenario 1.2 (total removal of stems > 25 cm) exhibited a 6-year recovery period and removed 49 trees without applying qualitative selection criteria. Scenario 3.1, applying multi-criteria selection, resulted in a lower immediate yield ($V_c = 8.68 \text{ m}^3$) with near-instantaneous structural recovery within 1 year.

In Property II, Scenario 1.1 required only one year to restore the initial stem density after the removal of 15 trees ($V_c = 7.41 \text{ m}^3$; $V_t = 11.55 \text{ m}^3$). A similar recovery period of 1 year was observed for Scenario 2.1, despite a significantly lower harvested volume ($V_c = 2.90 \text{ m}^3$), as this scenario targeted trees with compromised phytosanitary status. High-intensity extraction scenarios 1.2 ($V_c = 9.10 \text{ m}^3$) and 2.2 ($V_c = 9.53 \text{ m}^3$) yielded higher volumes but required longer recovery intervals of 6 and 4 years, respectively, to restore the original diameter distribution. Scenario 2.2 removed 26 trees with compromised stem quality or poor phytosanitary status, achieving the highest commercial volume for that property ($V_c = 9.53 \text{ m}^3$) with a recovery period of four years.

In Property III, Scenario 2.1 removed 27 trees characterized by poor stem quality, yielding a low timber volume ($V_c = 6.14 \text{ m}^3$; $V_t = 7.78 \text{ m}^3$) with a recovery period of 2 years. Scenario 1.2 removed 16 individuals with dbh > 30 cm, resulting in a substantially higher volume ($V_c = 10.54 \text{ m}^3$; $V_t = 13.95 \text{ m}^3$) and a recovery period of 4 years.

Scenario 3.1, which targeted trees with stagnant growth rates, produced the highest extraction levels for this site ($V_c = 11.41 \text{ m}^3$; $V_t = 15.02 \text{ m}^3$). Similarly, Scenario 4.1—based

on the balanced forest structures of De Liocourt and Meyer—involving the removal of 28 trees ($V_c = 10.22 \text{ m}^3$; $V_t = 13.46 \text{ m}^3$) while ensuring the retention of large-diameter legacy trees. Despite their high yields, both scenarios required an estimated recovery period of 4 years to restore the original stem density for classes above 25 cm dbh.

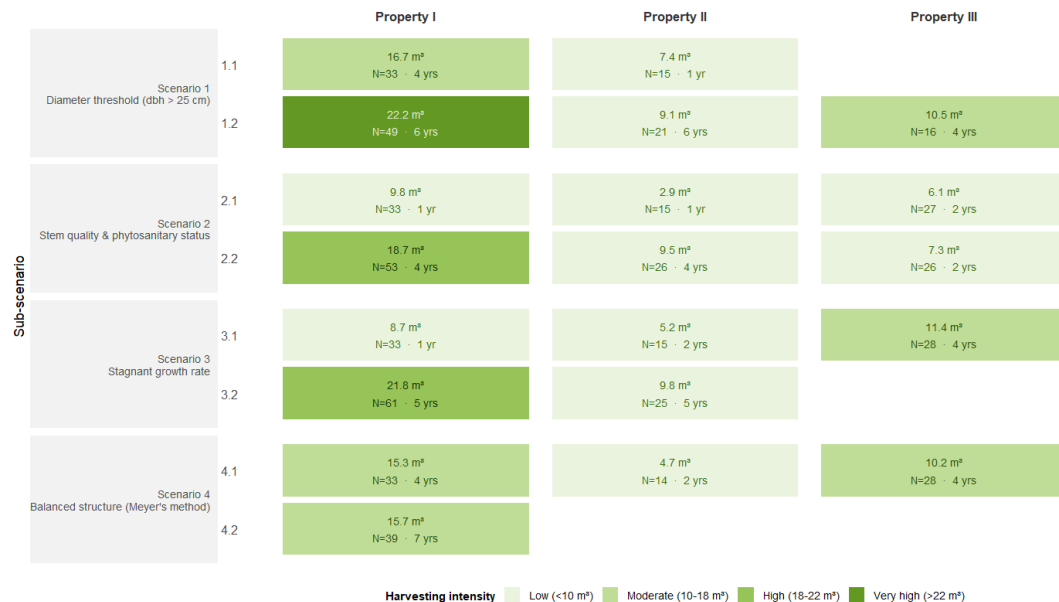


Figure 3. Simulated management scenarios for *Hovenia dulcis* across three properties in the Mixed Ombrophilous Forest, southern Brazil.

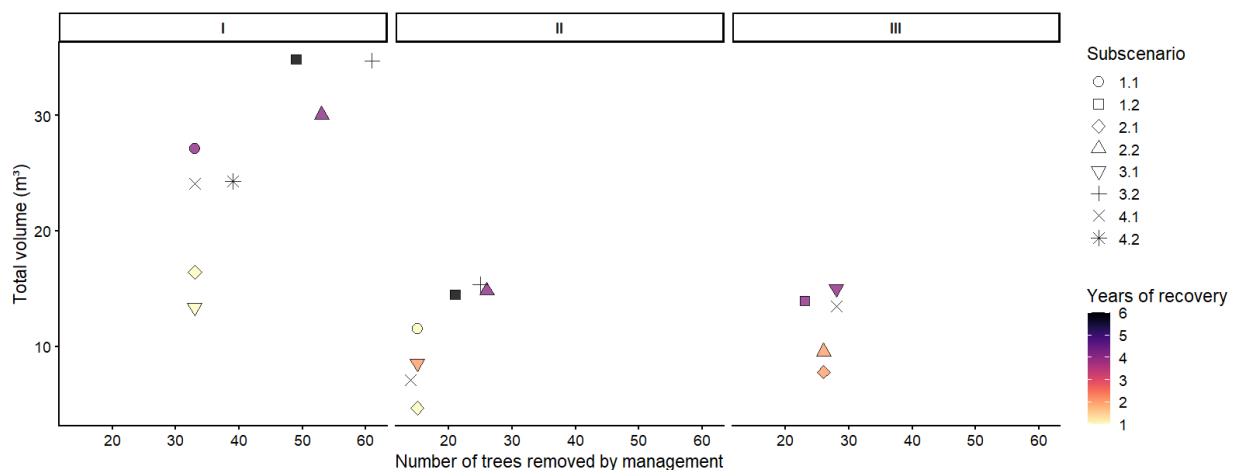


Figure 4. Relationship between the number of trees removed and total volume extracted (m^3) under different management scenarios across three properties invaded by *H. dulcis*.

Table 6. Quantitative summary of the scenarios after simulating the selection of trees from *Hovenia dulcis* to be removed in the management of sites.

Site/Property	Scenario	Subscenario	N	Vc	Vt	Time (Years)
I	1	1.1	33	16.73	27.09	4
		1.2	49	22.23	34.83	6
	2	2.1	33	9.77	16.43	1
		2.2	53	18.71	30.06	4
	3	3.1	33	8.68	13.41	1
		3.2	61	21.84	34.74	5
	4	4.1	33	15.26	24.10	4
		4.2	39	15.7		

II	1	4.2	39	15.68	24.31	7
		1.1	15	7.41	11.55	1
		1.2	21	9.10	14.46	6
	2	2.1	15	2.90	4.66	1
		2.2	26	9.53	14.86	4
	3	3.1	15	5.24	8.53	2
		3.2	25	9.75	15.35	5
	4	4.1	14	4.69	7.07	2
	III	1	1.2	16	10.54	4
		2	2.1	27	6.14	2
		2.2	26	7.30	9.57	2
		3	3.1	28	11.41	4
		4	4.1	28	10.22	4

N = number of trees removed by management; Vc = commercial volume removed; Vt = total volume removed.

Figure 3 summarizes the volume–recovery trade-off across all simulated scenarios and properties. The heatmap allows direct visual comparison of harvesting intensity—expressed as commercial volume extracted (Vc, m³)—alongside the number of trees removed (N) and the projected structural recovery period for each sub-scenario. Cells shaded in darker green represent higher extraction volumes and are consistently associated with longer recovery periods, regardless of the property or selection criteria applied. Property I displays the widest range of harvesting intensities, reflecting its higher invasion level and greater stem density, while Properties II and III are represented by fewer sub-scenarios and generally lower extraction volumes, consistent with their more preserved stand structures. Empty cells indicate sub-scenarios that were not applicable to the respective property due to insufficient stem density or diameter distribution to meet the prescribed selection criteria. The heatmap and Table 5 provide a comprehensive decision-support framework, enabling managers to identify the most appropriate management strategy for each site based on the desired balance between short-term economic return and structural recovery time.

Across all three properties, the simulated scenarios consistently revealed a trade-off between harvested volume and structural recovery time: higher extraction volumes were associated with longer recovery periods, regardless of the selection criteria applied. Property I, which presented the highest invasion level, also showed the greatest variability among scenarios, with commercial volumes ranging from 8.68 m³ (Scenario 3.1) to 22.23 m³ (Scenario 1.2) and recovery periods spanning from 1 to 7 years—reflecting the wider range of management options available when invasion intensity is high. Property II, despite having the lowest stem density among the three sites, achieved competitive commercial volumes under conservative harvesting, with recovery periods generally not exceeding four years, suggesting that more preserved stands can generate meaningful economic returns without requiring intensive intervention. Property III showed intermediate patterns, with the highest extraction scenarios (Scenarios 3.1 and 4.1) yielding volumes above 10 m³ with recovery periods of four years, comparable to the high-intensity scenarios in Property I despite lower overall stem density. Collectively, these patterns indicate that invasion intensity, rather than total stem density alone, is the primary driver of both the range of feasible management scenarios and the volume–recovery dynamics observed across sites.

4. Discussion

The structural attributes recorded in the 2022 census—mean dbh ranging from 18.72 to 20.78 cm, maximum dbh reaching up to 46.89 cm, and densities of 168 to 210 individuals across properties of 2.27 to 6.85 ha—indicate populations well beyond the early establishment phase, suggesting sustained competitive dominance in the invaded MOF stands. In its native range across China, Japan, and Korea, *H. dulcis* is described as a fast-growing species reaching 20–30 m in height, preferring sunny positions on well-drained, moist soils, and occurring primarily in secondary forests, disturbed habitats, and forest edges rather than in primary forest formations [2]. The maximum dbh values and stand densities observed in the present study are consistent with or exceed the structural parameters expected for mature native populations, suggesting that the species has reached full developmental expression—and possibly enhanced performance—in the invaded MOF stands. This pattern aligns with the well-documented tendency of invasive plant species to exhibit superior growth performance, larger size, and higher reproductive output in their invaded ranges compared to non-invasive congeners in their native ranges [2], likely reflecting the absence of co-evolved natural enemies, competitors, and biotic regulators that constrain population growth in the region of origin. The rapid ingrowth rates documented between 2018 and 2022 across all three properties further corroborate this interpretation, reinforcing the urgency of implementing structured management interventions before the invasion advances to higher-density stages.

The predictive model developed for the growth dynamics of *H. dulcis* demonstrated high performance, thereby supporting H1 and confirming its applicability as a decision-support tool for invasive species management across properties with contrasting forest structures. The strong predictive performance (marginal $R^2 = 0.89$, RMSE = 2.05 cm) can be attributed to the inclusion of key predictors well-established in the literature as drivers of individual tree growth: diameter at breast height from the previous measurement (dbhp), commercial height, crown projection area, and measurement period [9,21]. The dominance of dbhp as a predictor ($\beta = 0.919$) is consistent with the widely observed size-growth relationship in uneven-aged forests, where larger trees tend to sustain higher absolute growth increments owing to their greater access to light and resources. Together, these results confirm that objective (i)—developing a reliable, species-specific growth model for *H. dulcis*, was successfully achieved, and that the model is suitable for projecting future diameter distributions and timber volume under different management scenarios.

The use of linear mixed-effects models proved particularly appropriate for describing growth dynamics because they allow the simultaneous representation of fixed effects related to tree morphology and random effects associated with hierarchical forest structures, such as site conditions and measurement periods. Similar modeling approaches have been widely applied in forest growth studies to account for nested sources of variability and improve predictive accuracy [13,14,21]. In our case, the high residual variance observed indicates substantial individual-tree variability, which is consistent with findings in uneven-aged and heterogeneous forest stands where micro-site conditions, competition, and genetic variability strongly influence growth trajectories [22–24].

Despite the strong predictive performance observed, some limitations of the model should be acknowledged. The model was developed using data collected from specific forest sites in the state of Paraná, Brazil, which limits its direct applicability to other ecological contexts. However, the dataset used for model fitting included 447 observations covering diameter classes from 10 cm to approximately 40 cm dbh. This range encompasses nearly the entire diameter distribution reported for *H. dulcis* populations, which may reach up to approximately 45 cm dbh in naturalized stands [24]. Consequently, the model represents growth patterns across most developmental stages of the species. The broad representation of diameter classes increases the reliability of the model for describ-

ing species growth dynamics, since datasets covering wide ranges of tree sizes tend to improve the robustness and predictive accuracy of forest growth models. Therefore, although the model was calibrated using site-specific data, its structure and the wide diameter range represented suggest potential applicability for *H. dulcis* populations in similar forest conditions at other sites.

The growth patterns revealed by our model are consistent with the opportunistic and fast-growing behaviour widely associated with *H. dulcis* in Araucaria forest ecosystems. The strong dependence of diameter growth on previous dbh, crown area, and measurement period confirms that the species responds rapidly to competitive release, accumulating biomass at rates that facilitate the establishment of a dominant canopy layer across a wide range of diameter classes (10–40 cm). These dynamics are ecologically significant: by efficiently occupying canopy gaps and generating substantial understory shading, *H. dulcis* can suppress the regeneration of light-demanding native species of high ecological and economic importance, particularly *Araucaria angustifolia* [25]. The species' capacity to germinate and persist even under low light conditions [23], combined with its high abundance in fragmented landscapes and forest edges [24], further reinforces its competitive advantage over native regeneration and its potential to alter vertical forest structure, modify species composition, and contribute to the homogenization of forest communities.

From a silvicultural perspective, however, these same characteristics also create opportunities for management. The rapid growth and significant timber accumulation potential of *H. dulcis* indicate that its control can be integrated with productive forest management. By linking invasive species control with timber harvesting, it becomes possible to transform a major ecological challenge into an economic opportunity for smallholders, promoting both forest restoration and rural income generation.

Together, these results support H2 and confirm the validity of objective (ii): no single standardized management approach is appropriate for all properties invaded by *H. dulcis*. Rather, the contrasting stand densities, diameter distributions, and invasion intensities observed across Properties I, II, and III necessitated fundamentally different harvesting intensities and selection criteria to achieve comparable ecological and economic outcomes. This finding aligns with the broader principle that invasion impacts are mediated by landscape context and local biotic conditions [1–3,23], and reinforces the case for adaptive, property-specific management over generic prescriptions. A key contribution of this study is thus the demonstration that targeted tree selection based on growth performance, stem quality, and structural attributes, as evaluated through objectives (ii) and (iii), can simultaneously generate economic returns and improve stand dynamics. Rather than relying solely on generalized harvesting rules, the modelling framework allows management decisions to be tailored to the structural conditions of each property, supporting more efficient and ecologically informed interventions.

The simulated scenarios demonstrate that selective removal of *H. dulcis* individuals can be used not only as a strategy for controlling the invasion but also as a tool for restoring forest structure. The removal of trees with stagnant growth, large diameters, or low stem quality releases resources such as light, water, and nutrients for more vigorous individuals, while simultaneously increasing light penetration into the understory and promoting the establishment and growth of native regeneration. In forests where *H. dulcis* dominates the canopy, more intensive interventions may be necessary to break the light interception imposed by the invasive species and reactivate natural successional processes. In this sense, the planned harvesting of *H. dulcis* can be interpreted as a form of “invasion silviculture”, in which species control is integrated with restoration and sustainable production objectives.

Although *H. dulcis* is recognized as an invasive species, the complete elimination of all individuals is not always the most realistic or efficient strategy in fragmented agricul-

tural landscapes. In smallholder contexts, maintaining a controlled number of trees may provide direct economic benefits through the production of timber and fuelwood, as well as ecosystem services such as shading, habitat provision for generalist fauna, and soil protection. However, the persistence of this species should be strictly conditioned on management practices that prevent uncontrolled expansion, including defined cutting cycles, control of regenerating individuals, and prioritization of canopy openings that favor the regeneration of native species. In this way, adaptive management of *H. dulcis* can transform an ecological liability into a manageable resource, provided that native forest conservation goals remain the primary priority.

The adoption of higher-intensity scenarios in Properties I and III is further supported by the growth dynamics and invasion patterns described by previous studies [17,18]. The concept of “passage time”, defined as the period required for an individual tree to transition between diameter classes, is strongly influenced by light availability and competition [6]. When canopy openings are created through thinning or selective harvesting, passage time can be substantially reduced due to increased resource availability [26,27]. Consequently, removing stagnant large-diameter trees may accelerate the growth of remaining individuals and promote faster structural recovery. This mechanism also explains a key trade-off observed across scenarios: interventions targeting stagnant large-diameter trees, such as Scenario 3.2 in Property I (61 trees removed, 5-year recovery) and Scenario 3.1 in Property III (28 trees, 4-year recovery), achieved the highest volumetric yields precisely because they prioritized individuals with the greatest accumulated biomass. In contrast, scenarios with lower extraction volumes, such as Scenario 3.1 in Property I (33 trees, 1-year recovery), restored stand structure almost immediately but sacrificed short-term economic return. This volume–recovery trade-off is a critical variable for managers when designing cutting cycles, as it directly determines the interval between economically viable interventions.

In Property II, where invasion intensity was lower and stand structure more preserved, the most appropriate strategy was quality-oriented selection rather than volume maximization. Scenario 2.2, which prioritized the removal of 26 trees with compromised stem quality or poor phytosanitary status, achieved the highest commercial volume for that property ($V_c = 9.53 \text{ m}^3$) while limiting recovery time to four years. This result is consistent with silvicultural recommendations for uneven-aged forests, where thinning focused on stem quality and health has been shown to enhance long-term stand value and structural stability without compromising successional dynamics [24–27]. The contrast between the high-intensity approach required in Property I and the quality-driven strategy suited to Property II illustrates precisely why site-specific prescriptions are essential—a standardized protocol applied across both sites would either under-harvest in heavily invaded stands or over-exploit more conserved ones.

Furthermore, the intensive removal of trees in Property I is silviculturally justified by the high invasion level observed in MOF [7]. In forests where invasive species dominate the upper canopy, strong competition for light can suppress the regeneration of native species and alter ecosystem functions [25,28]. In such contexts, targeted removal of invasive individuals may be necessary to restore light availability and promote the recovery of native species such as *Araucaria angustifolia*.

The operational success of such interventions relies on specialized techniques, such as directional felling, to ensure minimal impact on natural regeneration below the critical thresholds observed in regional empirical studies [6,7]. Nauiack [7] observed that the weighted average of damage to native trees during *H. dulcis* harvest was extremely low—affecting less than 1% of the total stems per hectare. Such observations support the feasibility of integrating sustainable harvesting within ecologically sensitive areas, ensuring

that planned management of *H. dulcis* remains safe for natural regeneration and key native species.

Beyond technical constraints, the large-scale socio-economic implementation of these strategies faces significant barriers. On one hand, an established regional market exists; Nauaiack [6] demonstrated that sawlogs (dbh > 25 cm) can reach prices of approximately R\$ 150.00 per cubic meter, being 3.35 times more profitable than firewood. On the other hand, practical adoption is often hindered by limited access to specialized equipment for single-tree extraction and the complexity of selecting appropriate trees to harvest. Therefore, institutional support, including financial incentives and technical assistance, is essential to bridge the gap between theoretical models and practical field implementation [29].

Consequently, Continuous Cover Forestry (CCF) emerges as a viable strategy to mitigate the negative impacts of this invasive species while generating economic value for smallholders, provided that adaptive monitoring and institutional support are in place. Linking invasive species management with income generation may further stimulate public policy discussions regarding more flexible management approaches for native forests. Allowing regulated timber production may prevent the illegal conversion of forests to agricultural land or pastures, thereby contributing to the conservation of larger forest patches [6,28].

Finally, adaptive forest management and Forest Landscape Restoration (FLR) approaches are increasingly recognized as essential strategies for enhancing forest resilience under global environmental change [15]. While high-intensity harvest scenarios may challenge short-term resilience, strategies that prioritize the quality of remaining trees and consider long-term structural impacts are more likely to ensure forest sustainability [26]. Ultimately, improving regulatory frameworks to allow responsible management of Araucaria forests could benefit small farmers, who play a crucial role in conservation, and reduce incentives for deforestation [6,25,27].

5. Conclusions

This study demonstrates that sustainable management of *H. dulcis* in Mixed Ombrophilous Forest fragments is both ecologically justified and economically viable for smallholders operating under native forest legislation. The developed species-specific growth model, integrating diameter at breast height, commercial height, crown projection area, and measurement period, achieved strong predictive performance (marginal $R^2 = 0.89$, RMSE = 2.05 cm), thereby confirming H1 and validating its application as a decision-support tool for long-term silvicultural planning across properties with contrasting stand structures.

H2 was equally confirmed: no single standardized management strategy proved appropriate across all studied properties. Variations in invasion intensity, stand density, and diameter distribution among Properties I, II, and III required fundamentally different harvesting approaches to achieve comparable ecological and economic outcomes. In heavily invaded stands, high-intensity interventions targeting stagnant large-diameter trees maximized volumetric yield while reducing passage time for remaining individuals. In more preserved forests, quality-oriented selection prioritizing stem health and structural integrity proved more appropriate, enhancing long-term stand value without compromising successional dynamics.

A critical finding of this study is the volume–recovery trade-off inherent to all simulated scenarios: higher extraction volumes were consistently associated with longer structural recovery periods, ranging from 1 to 7 years depending on harvesting intensity. This relationship provides managers with a practical decision-making framework for design-

ing cutting cycles that balance short-term income generation with long-term forest functionality under Continuous Cover Forestry principles.

Taken together, these findings suggest that the planned harvesting of *H. dulcis* can function as a form of invasion silviculture, simultaneously controlling biological invasion, generating income for smallholders, and promoting the restoration of native forest dynamics. More flexible regulatory frameworks, combined with institutional support and technical assistance, are essential to translate these findings into field practice and transform the biological threat of *H. dulcis* into a manageable forest resource, contributing to the active conservation of biodiversity in the Mixed Ombrophilous Forest of Southern Brazil.

For the future recommendations, the findings of this study provide a foundation for implementing selective management of *H. dulcis* in native forests. However, to ensure the long-term success of these interventions, we propose a research agenda that our group intends to address in subsequent stages of the project:

- The first priority is the field application of the indicated scenarios. Post-harvest monitoring of these areas to validate the predicted growth rates and assess the real-world accuracy of the simulated recovery periods is needed.
- Future studies should investigate the direct impact of *H. dulcis* removal on the recruitment of native species, particularly *Araucaria angustifolia*. Understanding whether the disruption of the invasive canopy effectively restores native biodiversity is a vital step.
- Quantification of trade-offs between timber harvesting and carbon storage should be conducted. While *H. dulcis* grows rapidly, it is essential to determine how its removal and the subsequent growth of native species affect the forest's long-term carbon sequestration capacity.
- Following the findings on timber profitability, field surveys with local landowners to evaluate the socio-economic impact of these strategies on rural livelihoods and their willingness to adopt Continuous Cover Forestry (CCF) practices should be performed.

By addressing these questions, we aim to bridge the gap between theoretical modeling and the practical restoration of the Mixed Ombrophilous Forest, providing a robust framework for public policy and forest conservation in Southern Brazil.

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