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Predictive equations and operational recommendations for the extraction of *Pinus maestrensis* Bisse in the Guisa Forestry Unit

*Ecuaciones predictivas y recomendaciones operativas para la extracción de *Pinus maestrensis* Bisse en la Unidad Silvícola Guisa*

*Equações preditivas e recomendações operacionais para a extração de *Pinus maestrensis* Bisse na Unidade Silvícola Guisa*

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ABSTRACT

Logging in mountainous terrain is a critical operation that influences harvesting activities. Within this context, the present study aimed to develop percentile-based predictive equations and offer operational recommendations for the extraction of *Pinus maestrensis* Bisse in the Guisa Forestry Unit. To this end, the influence of three slope conditions (20-30%, 25-45%, 45-50%) and skidding distance on extraction time was evaluated using quantile regression. Two hundred and sixty-five extraction cycles were recorded in the field, and models were fitted for the 50th, 75th, and 90th percentiles. The results identified distance as the most determining factor, with increases of 0.101 to 0.132 min m⁻¹. Slope only showed a significant effect when it exceeded 45%, with increases of 3.2 to 4.9 minutes per cycle. On moderate slopes (25-45%), the effect was only significant in the slowest cycles (90th percentile). The generated equations constitute a tool for more efficient operational planning, contributing to reduced downtime and improved forest harvesting management in mountainous conditions.

Keywords: forest harvesting, slope, quantile regression, productivity, cycle time.

RESUMEN

La extracción forestal en terrenos montañosos es una operación crítica que influye en las actividades de aprovechamiento. En este marco, el presente estudio tuvo como objetivo desarrollar ecuaciones predictivas por percentiles y ofrecer recomendaciones operativas para la extracción de *Pinus maestrensis* Bisse en la Unidad Silvícola Guisa. Para ello, se evaluó mediante regresión cuantílica la influencia de tres condiciones de pendiente (20-30%, 25-45%, 45-50%) y la distancia de arrastre sobre el tiempo de extracción. Se registraron 265 ciclos de extracción en el campo y se ajustaron modelos para los percentiles 50, 75 y 90. Los resultados identificaron a la distancia como el factor más determinante, con incrementos de 0,101 a 0,132 min m⁻¹. La pendiente solo mostró un efecto significativo cuando superó el 45%, con aumentos de 3,2 a 4,9 min por ciclo. En pendientes moderadas (25-45%), el efecto solo fue significativo en los ciclos más lentos (percentil 90). Las ecuaciones generadas constituyen una herramienta para una



planificación operativa más eficiente, lo que contribuye a reducir tiempos muertos y mejorar la gestión del aprovechamiento forestal en condiciones de montaña.

Palabras clave: extracción forestal, pendiente, regresión cuantílica, productividad, tiempo de ciclo.

RESUMO

A extração florestal em terrenos montanhosos é uma operação crítica que influencia as atividades de aproveitamento. Neste marco, o presente estudo teve como objetivo desenvolver equações preditivas por percentis e oferecer recomendações operacionais para a extração de *Pinus maestrensis* Bisse na Unidade Silvícola Guisa. Para isso, foi avaliada por meio de regressão quantitativa a influência de três condições de pendência (20-30%, 25-45%, 45-50%) e a distância de arrasto em relação ao tempo de extração. Foram registrados 265 ciclos de extração no campo e ajustados modelos para os percentis 50, 75 e 90. Os resultados identificados à distância como o fator mais determinante, com incrementos de 0,101 a 0,132 min m⁻¹. O pendente solo mostrou um efeito significativo quando superou os 45%, com aumentos de 3,2 a 4,9 min por ciclo. Nos gastos moderados (25-45%), o efeito só foi significativo nos ciclos mais lentos (percentil 90). As economias geradas constituem uma ferramenta para um planejamento operacional mais eficiente, que contribui para reduzir os tempos mortos e melhorar a gestão do aproveitamento florestal em condições montanhosas.

Palavras-chave: extração florestal, pendente, regressão cuantílica, produtividade, tempo de ciclo.

INTRODUCTION

Extraction is a critical phase that determines the economic efficiency and environmental sustainability of timber harvesting (Grünberg *et al.*, 2023). This operation is particularly affected by sloping terrain, where technical factors such as the difficulty of moving equipment, greater mechanical wear, increased energy consumption, and the condition



of forest roads significantly reduce productivity and lengthen work cycles (Marcu and Borz, 2024).

Furthermore, the direction of uphill or downhill hauling imposes different operational demands that directly impact performance. Beyond operating costs, slope is a decisive factor in the environmental dimension. Steep inclines intensify the risks of erosion, soil compaction, and alteration of soil properties, especially under mechanized hauling operations, which compromises the ecosystem's regeneration capacity and promotes sedimentation processes (Ezzati *et al.*, 2021; Vintimilla, 2022). Therefore, planning for extraction in complex terrain should not only aim for productive optimization but also establish limits and techniques that mitigate soil degradation.

In this context, winch skidding is a widely used practice in developing countries, where terrain conditions make it difficult to use specialized machinery and operating costs are a determining factor; it offers an efficient and accessible solution for timber extraction, combines acceptable productivity with moderate investment, and becomes a strategic alternative for small-scale forestry operations (Gulci, 2020).

Optimization is therefore a key necessity for increasing the overall efficiency of the harvesting process. The negative effect of slope is well known; authors such as Ezzati *et al.* (2021) point out that in mountainous forests, felling and skidding productivity is higher on gentle slopes, with lower unit costs, while on steep slopes (>35%) productivity decreases and costs increase, so it is recommended to avoid operating under these conditions whenever possible.

Traditional modeling using ordinary least squares (OLS) relies on conditional mean estimation and offers a limited view of the relationship between variables, as it assumes that the effect of the predictors is constant across the entire response distribution. However, in complex systems such as forest ecosystems, this assumption is rarely met due to the inherent heterogeneity and heteroscedasticity of the data (Campos Frühauf *et al.*, 2024).



Given this limitation, quantile regression emerges as a robust alternative, as it allows us to "model more than just the mean: it estimates the relationship between predictors and different quantiles (percentiles) of the response variable (e.g., high vs. low growth), offering a complete view of the conditional distribution, not just the mean value" (Lansanova *et al.*, 2021). Its ability to capture differentiated relationships across the distribution, such as the variable effect of slope according to cycle speed, makes it an ideal tool for addressing the objectives of this study.

The objective of this study was to develop percentile-based predictive equations and operational recommendations for the extraction of *Pinus maestrensis* in the Guisa Forestry Unit, using quantile regression models. These tools will allow for more efficient planning of extraction times by considering operational variability based on slope and skidding distance.

MATERIALS AND METHODS

The research was developed in the management area called "Los Números", in *Pinus maestrensis* plantations belonging to the Guisa Silvicultural Unit of the Granma Forestry Company, located in the eastern region of Cuba (Figure 1).

This territory is characterized by a rainfall regime that ranges between 1,600 and 1,900 mm annually, according to official records provided by the Ministry of Science, Technology and Environment of Granma (CITMA, 2025). These conditions significantly influence growth dynamics and forestry operations.

The area has a varied topography, with slopes that directly influence the efficiency of extraction operations, the central aspect of this study. Data collection took place between October and December 2024, during full working days; data were recorded continuously. extraction cycle times and the Drag distances associated with each slope condition. This period allowed for obtaining representative information on the operational and environmental conditions, ensuring the validity of the results for evaluating the impact of slope on the productivity of forest harvesting.



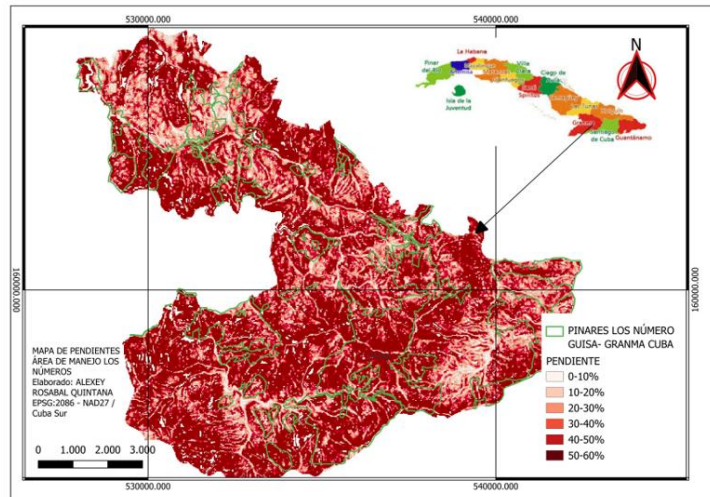


Figure 1. - Slope map of the “Los Números” management area

Definition and classification of slope conditions

In the analysis of forest extraction, three slope categories were defined: slope 1 (20–30%), slope 2 (25–45%), and slope 3 (45–50%). This classification allows for the selection of the most appropriate harvesting system according to FAO recommendations (Dykstra and Heinrich, 2018).

On gentle slopes (20–30%), the operational limit corresponds to traditional systems using draft animals (oxen), especially for downhill hauling, where exceeding 30% is not recommended to avoid risks and soil damage. On moderate slopes (25–45%), the capacity of animals and conventional tractor hauling is exceeded; therefore, cable systems with winches are more suitable, as they reduce compaction and erosion by avoiding the direct passage of machinery on steep slopes. Finally, on steep slopes (45–50%), land-based systems cease to be safe and sustainable, requiring specialized technologies.

Studio design

To assess the influence of terrain slope on the forest extraction cycle time, an observational time and motion study was conducted over a three-month period (October–December 2024). This period constitutes a continuous record representative of the usual operating conditions of the Guisa Forestry Unit. The observation unit was



defined as a complete extraction cycle, from log stockpiling at the felling point to unloading at the loading area.

In order to ensure comparability between cycles, strict experimental control criteria were established: all operations were carried out with the same extraction equipment (KrAZ-255B truck with front winch), under homogeneous climatic conditions (without heavy rainfall) and during work shifts of comparable duration.

Equipment and materials

Extraction equipment. A 1987 KrAZ-255B forestry truck equipped with a front winch was used for the operations. This model incorporates a 14.9 L YaMZ-238 V8 diesel engine (240 hp/180 kW), coupled to a 5-speed YaMZ-236N manual transmission. The vehicle has an unladen weight of approximately 12 tons and dimensions of 8.65 m in length, 2.75 m in width, and 2.94 m in height. Its 6x6 drive configuration, wide tires (1300 × 530 × 533 mm), and two-door metal cab make it suitable for challenging terrain.

The winch system, mounted on the front of the chassis, is driven by an auxiliary transmission connected to the engine and has an approximate pulling capacity of 15 t. It uses high-strength braided steel cable, with a diameter of 18–20 mm and a length of 100 m.

Sample size and classification by slope

265 extraction cycles were recorded, which were *subsequently classified* into three slope categories according to the FAO classification (Dykstra and Heinrich, 2018) and by category they were:

- Slope I (20–30%): 114 cycles.
- Slope II (25–45%): 66 cycles.
- Slope III (45–50%): 85 cycles.

The number of cycles per category reflects the proportion of operations performed on each type of slope during the study period. For each cycle, the total time in minutes was recorded and the associated drag distance was measured (range: 40–240 m).



Verification of sample sufficiency

Sampling

simple random sampling was carried out during the study period (October–December 2024), recording all extraction cycles completed during working days under the usual operating conditions of the Guisa Forestry Unit. The formula for infinite populations used in different forest harvesting and inventory studies was applied (Lanz *et al.*, 2019):

$$n = \left(\frac{Z * \delta}{E} \right)^2$$

A 90% confidence level ($Z_{\alpha/2} = 1.645$) and a maximum acceptable margin of error of 10% with respect to the estimated mean, which is based on the high variability inherent in forest productivity studies in tropical conditions, where it is common to accept between 10% and 20% due to the influence of uncontrollable factors (Heinrich, 1993).

Once the sample sufficiency was verified, the construction of the quantile regression models was carried out using all 265 cycles recorded in the field (114, 66 and 85 cycles, respectively), which allowed taking advantage of all the variability observed in the extraction operations.

Measured variables and field procedure

total extraction time was considered the dependent (response) variable, as it is the direct measure of operational performance. The independent (predictor) variables were the slope of the terrain, categorized into three levels according to the FAO classification: I (20–30%), II (25–45%) and III (45–50%); and the drag distance recorded in meters as a continuous variable.

The following were used to record the variables: digital stopwatches to measure cycle time (min), clinometer to determine the slope (%) and Nikon Forestry Pro laser hypsometer to measure the drag distance (m).



Statistical analysis

A descriptive analysis was performed to characterize the distribution of extraction times under each slope condition. Measures of central tendency and dispersion (mean and standard deviation) were calculated using SPSS version 25 software.

Quantile regression was used to estimate the relationship between cycle time (dependent variable) and the predictor variables (slope and distance). This method allows for obtaining predictive equations for different percentiles of the extraction time distribution, unlike ordinary least squares models, which only estimate the conditional mean effect. This choice is due to the nature of forest data, which exhibit high variability and heteroscedasticity, conditions under which quantile regression is particularly robust because it does not assume constant variance (Ajao *et al.*, 2023).

Furthermore, this technique overcomes the limitations of mean-based models, as it estimates the relationship between predictors and different percentiles of the extraction time distribution (e.g., medium-length cycles vs. exceptionally slow cycles), thus providing a more comprehensive view of the operational phenomenon (Hird *et al.*, 2024). Its ability to capture differentiated relationships across the distribution makes it the ideal tool for addressing the objectives of this study.

The models were estimated in the R environment (version 4.5) with the *quantreg* package, specified as follows:

$$Q_{\tau}(\text{Tiempo}) = \beta_0(\tau) + \beta_1(\tau) \cdot \text{Pendiente} + \beta_2(\tau) \cdot \text{Distancia}$$

Where $Q_{\tau}(\text{Tiempo})$ represents the *quantile* τ of the extraction time distribution conditioned on the values of the independent variables. Models were estimated for the *quantiles* $\tau = 0.50$ (*median*), 0.75 , and 0.90 . The parameters $\beta(\tau)$ and their confidence intervals were obtained using a *bootstrap procedure* with 1,000 replicates, which ensures robust estimates against possible deviations from classical assumptions.



RESULTS AND DISCUSSION

Descriptive analysis of extraction times and distances

Table 2 presents the descriptive statistics. The highest mean time corresponds to slope III (45–50 %), while slope II (25 – 45 %) shows the lowest mean and least dispersion, suggesting more homogeneous operating conditions. Although the slope I (20 – 30 The %) is the smoothest, exhibiting the greatest variability (standard deviation and range), indicating that the drag distance, with maximum average and dispersion in this category, is a determining factor. The average distances on slopes II and III are similar; however, their times differ, demonstrating the additional effect of the incline on the difficulty of the operation.

Table 2. - Descriptive statistics of extraction time (min) and drag distance (m) by slope condition

| Condition | n | Time (min) | | | | Distance (m) | |
|--------------|-----|------------|------|------|-------|--------------|-------|
| | | Average | OF | Min | Max | Average | OF |
| I (20–30%) | 114 | 14.35 | 8.69 | 3.98 | 35,37 | 140.9 | 76.6 |
| II (25–45%) | 66 | 13.49 | 6.79 | 4.23 | 32.00 | 126.7 | 56.2 |
| III (45–50%) | 85 | 16.88 | 7.05 | 4.78 | 36.85 | 132.7 | 59.7 |
| Total | 265 | 14.94 | 7.84 | 3.98 | 36.85 | 133.9* | 65.2* |

***Global mean and standard deviations (SD) of distance (calculated from 265 cycles)*

The overall dispersion of times (total SD = 7.84 min; range = 3.98–36.85 min) and intracondition variability confirm the existence of conditioning factors beyond the slope, primarily the drag distance.

Quantum regression: methodological advantages and model results

Table 3 presents the estimated coefficients for each predictor in the three percentiles analyzed, along with their significance level and the pattern observed throughout the distribution.



Table 3. - Coefficients of the quantile regression models for extraction time (min) as a function of slope and distance

| Preacher | $\tau = 0.50$ | $\tau = 0.75$ | $\tau = 0.90$ | Pattern |
|---------------------------------|---------------|---------------|---------------|--------------------|
| Distance (min m ⁻¹) | 0.101*** | 0.115*** | 0.132*** | Growing |
| Slope 2 (min) | 0.209 | 0.920 | 1,380** | Emergent |
| Slope 3 (min) | 3,246*** | 4,206*** | 4,913*** | Intense increasing |

*** $P < 0.001$; ** $P < 0.01$

Quantile regression models revealed a differentiated structure in the influence of predictor variables on forest extraction time. Equations for the 50th, 75th, and 90th percentiles were obtained from these models; their graphical representations are shown in Figure 2, where the increasing effect of distance and slope on cycle time is evident. Based on these models, three fundamental trends were identified.

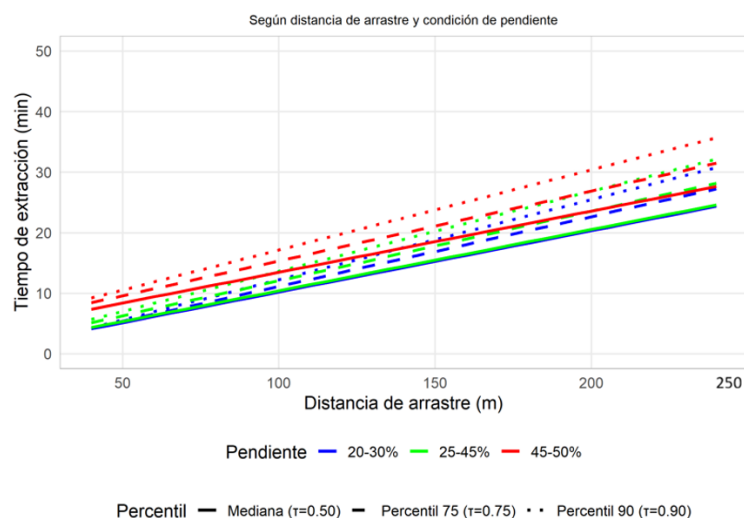


Figure 2. - Curves obtained for the percentiles

- Drag distance emerged as the most consistent and significant factor, with positive coefficients in all quantiles ($P < 0.001$ in all cases) and a linear effect that progressively intensifies in the upper percentiles: from 0.101 min m⁻¹ at the median ($\tau = 0.50$) to 0.132 min m⁻¹ at the 90th percentile ($\tau = 0.90$) (Table 3).
- The slope category showed stratified behavior: while Slope 3 (45-50%) had highly significant effects across the entire distribution, Slope 2 (25-45%) only reached statistical significance in the highest quantiles.



- The magnitude of the effects increased systematically as we moved up the distribution, indicating that in slower operations (upper quantiles), both distance and slope exert a more severe temporal increase.

Analysis by specific quantiles

50th percentile (median)

Under the most frequent operating conditions, it was observed that each additional meter of distance increased the median time by 0.101 min (\approx 6 seconds), with a highly significant effect ($P < 0.001$). Similarly, the presence of extreme slopes ($> 45\%$, classified as Slope 3) resulted in an increase of 3.246 min in the median time compared to gentle slopes (20–30%, Slope 1), also with high statistical significance ($P < 0.001$).

In contrast, moderate slopes (25–45%, Slope 2) showed no statistically significant differences compared to gentle slopes ($P = 0.643$). From an operational perspective, these results indicate that the transition to extreme slopes implies an increase of more than three minutes per cycle, while moderate slopes do not represent a relevant increase in operating times under normal conditions.

75th percentile = 0.75 (75th percentile)

In the slowest operations in the upper quartile, a growing impact per unit of distance was observed, reaching 0.115 minutes per meter traveled, which is 14% higher than the effect observed in the median. Under these conditions, the influence of the slope intensifies significantly: extreme slopes ($>45\%$, classified as Slope 3) increased the median time by 4.206 minutes compared to gentle slopes (Slope 1), with high statistical significance ($P < 0.001$).

Moderate slopes (25–45%, Slope 2) showed a marginally significant effect of 0.920 min ($P = 0.069$), suggesting that, in slow-operation scenarios, even intermediate slopes can contribute to additional delays. From an operational perspective, these findings confirm that both distance and slope become critical factors in longer cycles, reinforcing the need for planning strategies that consider scenarios with greater time constraints.



Percentile = 0.90 (90th percentile - Slowest operations)

The highest sensitivity to distance was observed in the longest 10% cycles, with an increase of 0.132 minutes per meter traveled (equivalent to 7.9 seconds), representing a 31% increase compared to the median. Under these extreme conditions, the influence of the slope also reached its greatest intensity: extreme slopes (>45%, classified as Slope 3) added 4.913 minutes to the operating time, while moderate slopes (25–45%, Slope 2) showed a clearly significant effect for the first time, with an increase of 1.380 minutes ($P = 0.007$).

From an operational perspective, these results confirm that, in the most unfavorable scenarios, each factor acts with maximum intensity; even moderate slopes acquire practical relevance in prolonging cycles.

The ability of quantile regression to reveal differentiated relationships across distribution has been highlighted in recent forestry studies. Dong *et al.* (2025), modeling self-randomization lines in larch plantations, found that the effects of site quality and aridity varied significantly between percentiles, which would not be detectable with mean models.

Along these same lines, Patidar *et al.* (2023) demonstrated that, while *machine learning models* can offer greater predictive accuracy, quantile regression retains the advantage of providing interpretability regarding how factors differentially affect segments of the distribution. The present study confirms this advantage: while distance showed a constant and increasing effect across all percentiles, similar to the pattern observed by Axer *et al.* (2025) in the distance-regeneration density relationship, slope exhibited a threshold behavior that only manifests under extreme conditions.

In the field of forest characterization, percentile regression methods have been employed in various branches. Pérez *et al.* (2019) used them to estimate diameter distributions in *Pinus patula* Schltdl., facilitating parameter estimation without numerical integration procedures. In the field of forest harvesting productivity, recent studies have also applied quantile regression to model cycle times as a function of topographic and operational variables (Ezzati *et al.*, 2021; Marcu and Borz, 2024), which supports its relevance to this study.



Implications for operational management

Predictive equations were developed based on the quantile regression models. specific to each percentile of interest

For the median ($\tau = 0.50$):

$$\text{Time} = 0.077 + 0.209 \cdot P2 + 3.246 \cdot P3 + 0.101 \cdot \text{Distance}$$

For the 75th percentile ($\tau = 0.75$):

$$\text{Time} = -0.398 + 0.920 \cdot P2 + 4.206 \cdot P3 + 0.115 \cdot \text{Distance}$$

For the 90th percentile ($\tau = 0.90$):

$$\text{Time} = -1.003 + 1,380 \cdot P2 + 4,913 \cdot P3 + 0,132 \cdot \text{Distance}$$

For time planning

The operational analysis identified that, on slopes exceeding 45%, it is necessary to allocate between 3 and 5 additional minutes per cycle, depending on the planning percentile considered. In the case of moderate slopes (25-45%), conservative scenarios suggest incorporating up to 1.4 extra minutes, highlighting its potential impact under demanding conditions.

On the other hand, reducing the distance also showed significant effects: each 10-meter decrease resulted in time savings of between 1.0 and 1.3 minutes, depending on the slope of the terrain where the operation is carried out. These results reinforce the importance of integrating both slope and distance into planning models in order to anticipate increases in forest harvesting times.

In this regard, Szewczyk *et al.* (2025) suggest that slope influences forest harvesting: on gentle slopes ($\leq 20\%$), operations are quick and efficient; on moderate slopes (20-40%), effort and time increase due to safety concerns; and on steep slopes ($> 40\%$), specialized methods are required, which increases the duration of operations and reduces productivity. These results coincide with those observed in the Guisa Forestry Unit, where slopes exceeding 45% showed the greatest increases in extraction time.



For the design of extraction systems

The results obtained technically validate the classification proposed by the FAO, confirming that slopes exceeding 45% require the implementation of specialized systems to ensure operational efficiency. In the moderate slope range (25-45%), conventional systems are viable, although with longer timeframes that must be considered in the planning. Finally, it was shown that optimizing distances generates greater returns precisely in steep slope scenarios, reinforcing the need to integrate distance reduction strategies as an essential complement to forest harvesting in complex terrain.

On steeper terrain, the transport and operation of machinery become less efficient, and risks increase, resulting in higher maintenance and safety costs. This geomorphological condition significantly raises operating costs, affecting the profitability of forestry operations (**Martínez - Cantón et al., 2022**).

For operational risk analysis

Applying the quantile distribution allowed us to identify the presence of heavy tails in the operating times, highlighting the existence of extreme scenarios relevant to management. In this regard, the 75th and 90th percentiles serve as useful references for conservative planning and worst-case analysis. Furthermore, the significant appearance of Slope 2 at $\alpha \tau = 0.90$ reveals hidden risks in moderate slopes, which are not apparent under average conditions but become significant in longer cycles.

These results are supported by previous applications of quantile regression in forestry, where this methodology has allowed for the modeling of extremes in growth, survival, and biomass, as well as the anticipation of critical scenarios such as fires or natural regeneration. As in those studies, the identification of heavy tails, the use of high percentiles, and the detection of hidden risks under moderate conditions confirm the value of quantile regression as a robust tool for revealing invisible patterns in the mean and strengthening planning in complex contexts (Antúnez et al., 2025).



CONCLUSIONS

Drag distance proved to be the most influential factor in extraction time, with an effect that intensifies in the higher percentiles.

The slope only showed a significant impact when it exceeded 45%, while in the moderate range (25-45%) its effect was only relevant in the slowest cycles (90th percentile).

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