

A Work Project, presented as part of the requirements for the Award of a Master's degree in
Business Analytics from the Nova School of Business and Economics.

Economic Sustainability Models for Land Uses on Rural Territory

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Abstract

This thesis evaluates the economic viability of five land-use systems - maritime pine, eucalyptus, cork oak, olive groves, and solar panels - through growth, financial, and geospatial modelling. For forestry cultures, APIs linked to StandsSIM and SUBER 5.0 simulators were used to simulate and assess profitability of Mação's management approach and provide recommendations. Olive groves were assessed across three cultivation systems to balance profitability and sustainability. Solar farms were evaluated using GIS and financial models, identifying optimal sites based on socio-environmental, location and climate. Findings highlight strategies for sustainable resource use, improved land-use practices, and renewable energy development in Mação.

Keywords

Business Analytics, Territory Sustainability, Economic Models, Forest, Wildfires

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1. Introduction

This first chapter introduces the document and is divided into three sections. The first section describes the origin of the project, the context in which it is situated, and the motivation for its development. The second one presents the problem addressed and summarizes the approach used to resolve it. Finally, the third and last section discusses the organization of this document.

1.1 Motivation and Context

Historically, in the 1950s and 1960s, the agro-silvo-pastoral systems that characterized rural areas maintained a multifunctional landscape from both economic and ecological perspectives. However, with significant population exodus, most of the territory was abandoned and left unmanaged, leading to the widespread accumulation of vegetation, serving as fuel for wildfires.

Mação, a Portuguese region located in the district of Santarém, is a living example of these challenges. This Portuguese territory covers 41,000 hectares and is divided into 80,000 properties owned by 20,000 individuals, averaging 0.7 hectares (Médio Tejo 2019). Since most property owners left their land unmanaged, the territory has become highly vulnerable to fires.

Over the past 30 years, Mação's municipality has seen its territory being devastated by wildfires. Between 1991 and 2019, large wildfires burned a significant proportion of the territory, the most severe ones being those that took place in 2003, 2017, and 2019 (Fernandes et al. 2020). In 2017 (ICNF 2017), 27,000 hectares were affected by wildfires, corresponding to 67% of the territory's area. In 2019, although the burned area was smaller compared to 2017, the wildfires affected the areas that had not burned in the previous wildfire, leaving a total of 90% of the territory affected (ICNF 2019). These numbers show the necessity of changing the current design of the rural landscape to reduce the fire vulnerability of this Portuguese territory.

Currently, in response to these challenges, Mação has developed 9 Integrated Landscape Management Areas (AIGP) (Câmara Municipal de Mação 2021). These areas are designed with

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the objective of promoting sustainable landscape management through collective agroforestry exploitation, especially in areas with a high risk of wildfires. Each AIGP includes the development of Integrated Landscape Management Operations (OIGP), consisting of strategies for landscape transformation, territorial enhancement, and revitalization. They also address practical aspects including financing, management, and monitoring ensuring long-term success.

These operations are detailed through two key maps: the POSA (Current Land Use Map) and the POSP (Proposed Land Use Map). The POSA documents the existing land use, while the POSP outlines the planned changes, focused on reducing wildfire risks, improving ecosystems, and revitalizing the local economy. It follows a transformation strategy based on the natural characteristics of the territory and land suitability, following preventive forestry laws and territorial programs. The POSP includes the proposed land use units (based on the COS 2018 nomenclature, a land occupation map that provides a structural view of the territory), the ecological and resilience structures and the structural elements, such as notable landmarks, hedges, walls, terraces, and infrastructure necessary for landscape transformation and management. The landscape transformation matrix compares the POSA with the POSP, providing a summary table showing the variation of values across different land use categories.

In total, AIGPs cover 20,209 hectares which corresponds to around 50% of the municipality's total area (Matias 2023). Within these areas, conditions will be created for the development of OIGPs, executed by a collective management model overseen by a managing entity. The OIGPs are supported by a long-term, multi-fund program that provides financial backing for initial investments and ongoing management activities (Câmara Municipal de Mação 2021).

To design and implement these AIGPs it is essential to assess the medium and long-term economic sustainability of the proposed landscape models. This project's objective is to address this challenge by studying, implementing, and evaluating the most efficient models available

in the literature for the AIGPs. These will be integrated into the LAND IT system (Computer-Aided System for the Design of Integrated Territory Management), currently being developed in a partnership between NOVA School of Science and Technology and AZR - Gestão Territorial, S.A., a company established in Mação that manages the AIGP of Mação and is responsible for developing its Integrated Landscape Management Operation (OIGP). A more detailed explanation on the LAND IT platform can be found in Section 3.

1.2 Objectives and Approach

This thesis integrates various approaches to model and analyze the economic and environmental performance of five selected land use systems: maritime pine, eucalyptus, cork oak, olive groves, and solar panels. The order of analysis reflects the temporal scale, progressing from long term forestry crops (maritime pine, eucalyptus, and cork oak) to a one-year agricultural system (olive groves), and finally to solar panels. Forestry systems prioritize sustainability and profitability over extended timelines, while agricultural systems aim to optimize yields, and solar panels focus on site feasibility and financial modelling to maximize energy production.

I. Forest Species – Maritime Pine, Eucalyptus and Cork Oak

The StandsSIM simulator served as the foundation for the development of a growth and economic model for both eucalyptus and maritime pine, while cork oak modelling was based on SUBER 5.0. To enhance usability, APIs were created for each species, to integrate these models into the LAND IT platform. The APIs enable users to customize simulations by inputting parameters such as tree density and planning horizon, generating tailored outputs like cash flow projections and operational costs. To provide practical guidance for sustainable forest management, both univariate and multivariate sensitivity analyzes were conducted so that optimal management strategies could be identified.

II. Olive Tree

The analysis of olive tree cultivation focuses on three distinct systems: traditional, potted, and hedge. The model is built on practical inputs, including annual maintenance costs, installation expenses, olive oil market price and yield dynamics, that are going to vary according to the age of the olive grove. The main goal of the developed model is to provide actionable recommendations that balance profitability with sustainability practices in olive production.

III. Solar Panels

The feasibility of utility-scale solar farms was assessed through a combination of geospatial and financial modelling. Using Geographic Information Systems (GIS), 16 polygons from the OIGP database were evaluated based on criteria such as slope, solar radiation, and proximity to substations. This analysis shortlisted four viable sites, which were further analyzed. Financial models integrated investment costs and operational expenses with the objective of identifying the most economically viable options for renewable energy development.

1.3 Document Structure

This thesis is structured into nine sections, each addressing specific parts of the research. The first section introduces the motivation, context, and objectives of the study, highlighting the challenges addressed, and the methodologies applied to achieve the thesis' main objectives. It concludes with this overview of the document structure. The second section focuses on Mação's geography and territorial characteristics, as well as the relevance of the AIGPs. The third and fourth introduce and give key insights regarding both LAND IT and sIMfLOR, respectively. From the fifth to seventh section the maritime pine, eucalyptus, and cork oak are analyzed, respectively. These sections present the development of an API, sensitivity analyzes, and recommendations for sustainable management practices. Section eight analyzes olive trees, and its different cultivation systems to evaluate their economic and operational performance in

Mação, while the ninth section evaluates the feasibility of solar farms, incorporating geospatial and financial modelling to optimize site selection and assess economic viability.

2. Mação

This chapter provides a detailed analysis of Mação, focusing on its location, territorial characteristics, and implementation of AIGPs (Integrated Landscape Management Areas).

2.1 Mação's Location and Territory Characteristics

Mação, located in the district of Santarém, lies at the geometric center of Portugal, and spans approximately 41,000 hectares. Figures 2.1 and 2.2 show the most recent land use cartography (COS 2018), and that the predominant land use is forestry, marked in green in Figure 2.1, with maritime pine and eucalyptus dominating the landscape with 48.6% and 27.7%, respectively. On the other hand, agricultural lands, including olive groves occupy smaller areas, accounting for 4.89%, represented in orange, while buildings and roads are represented by red polygons.

Additionally, Mação is divided into six parishes: Amêndoa, Cardigos, Carvoeiro, Envendos, Mação, Penhascoso, Aboboreira, and Ortiga. These geographic features define a diverse landscape but with challenges related to land management and environmental sustainability.

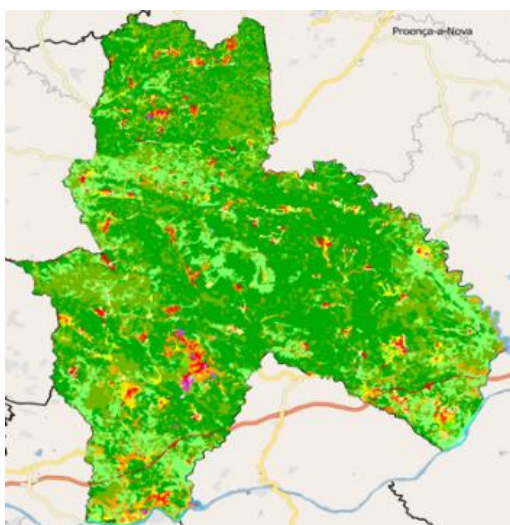


Figure 2.1: COS Map | Source: [Matias 2023](#)

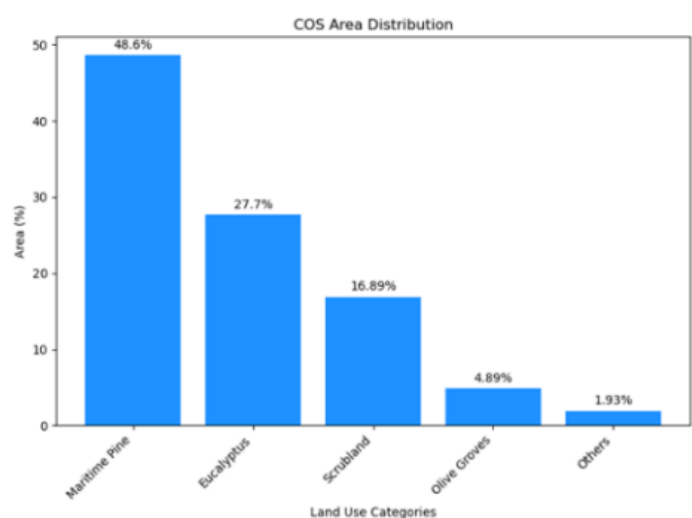


Figure 2.2: COS Area distribution

The topography of Mação is highly varied with more than 55% of the terrain exhibiting slopes between 5° and 15°, which makes the area prone to erosion and increases the risk of wildfire propagation, especially in steeper regions. Also, the hypsometry further highlights its varied land with 50% of the area situated 250–350 meters above sea level (Figures 2.3 and 2.4).

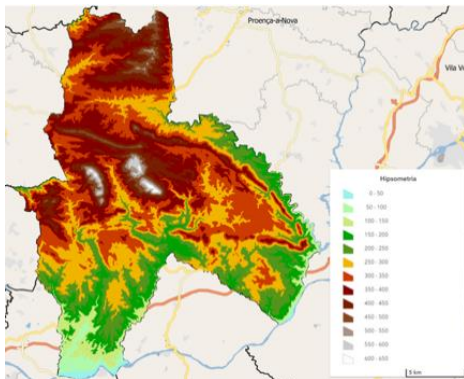


Figure 2.3: Hypsometry in Mação

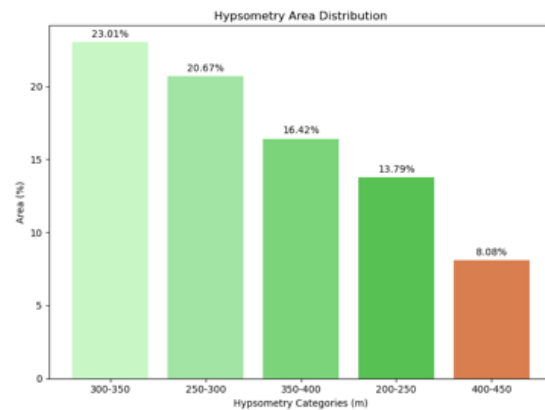


Figure 2.4: Map Hypsometry in Mação | Source: [Matias 2023](#)

These physical characteristics, combined with abandoned properties, biomass accumulation, and high summer temperatures exacerbated by climate change, make Mação one of Portugal's most wildfire-prone zones. Figures 2.5 and 2.6 show that 60% of its territory is classified as high or very high fire risk.

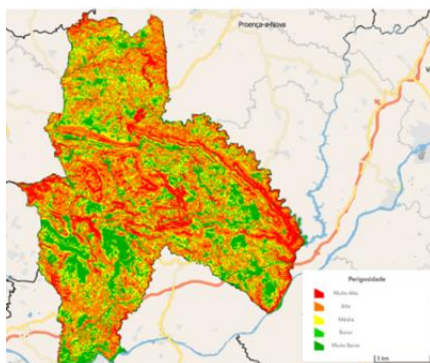


Figure 2.5: COS Hypsometry in Mação

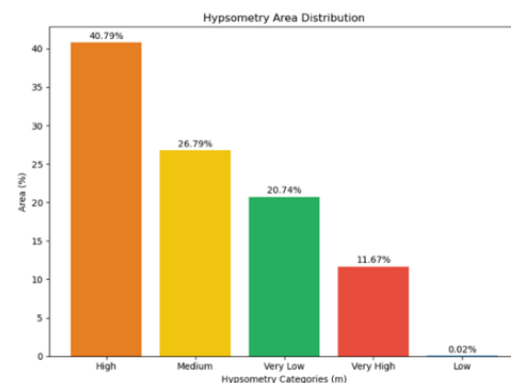


Figure 2.6: COS Map Mação | Source: [Matias 2023](#)

2.2 Mação's AIGPs

Mação has established nine AIGPs: Aboboreira, Amêndoa, Cardigos, Carvoeiro, Castelo, Envendos, Mação, Ortiga, and Penhascoso, which cover approximately 20,209 hectares or about 50% of the municipality's total territory. These AIGPs are a response to the critical need to reduce wildfire vulnerability while aiming to promote environmental, social and economic

sustainability. This project focuses on analyzing four AIGPs: Amêndoa, Ortiga, Castelo, and Carvoeiro, which were selected by the Municipality of Mação for their strategic importance.

2.3 POSA and POSP: Current and Proposed Landscape Design

Mação's strategy for landscape management relies on two essential tools: the Current Land Use Map (POSA) and the Proposed Land Use Map (POSP). POSA provides a detailed overview of the current land use, revealing the dominance of maritime pine and eucalyptus forests, while agricultural areas, such as olive groves are presented in a smaller portion. This distribution reflects historical land management patterns, heavily focused on forestry, which has contributed to the region's economic activities. However, this increases vulnerability to wildfires, given the high flammability of these species. Figure 2.7 shows the areas occupied by the cultures under study in each AIGP. The POSP presented in Figure 2.8, shows the proposed changes to Mação's landscape, aiming to address the fire hazards and ecological imbalances identified in the POSA. A key change is the reduction of maritime pine and eucalyptus forests in favor of fire-resistant vegetation, such as cork oak forests and agroforestry systems. These adjustments aim to diversify land use, integrating sustainable agricultural practices and increasing the coverage of olive groves and cork oak forests, which offer greater ecological resilience and economic value. Additionally, the POSP introduces innovative land uses, such as renewable energy projects of solar farms to enhance economic productivity while reducing dependence on common forestry.

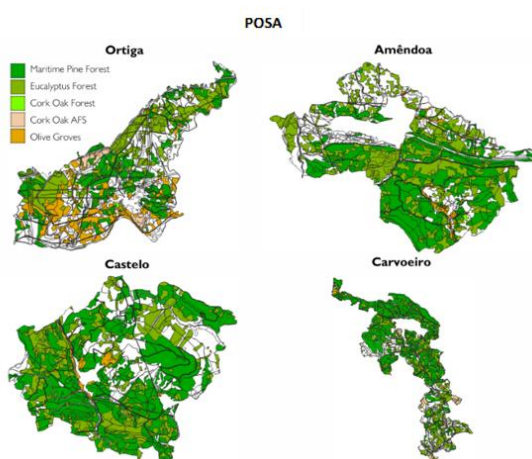


Figure 2.7: Current Land Use Map in four specific AIGPs

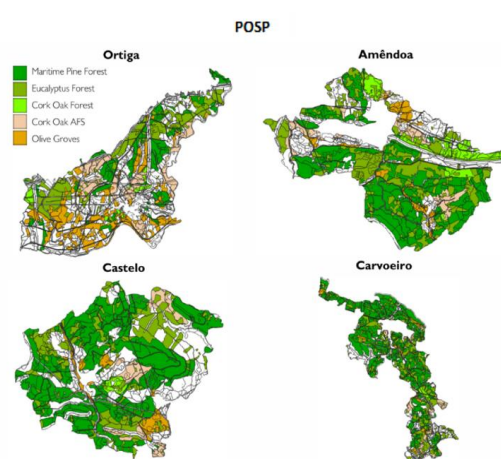


Figure 2.8: Proposed Land Use Map in four specific AIGPs

3. LAND IT Platform

The creation of an OIGP is a highly detailed and iterative process that was designed to address challenges in land-use planning in territories identified as vulnerable in the AIGP ([DGT 2023](#)). [LAND IT](#) creation emerged to solve the inefficiencies associated with OIGPs creation. It consists of a Decision Support System that integrates advanced geospatial tools and data-driven decision-making capabilities, in order to save time and reduce errors when developing an OIGP.

LAND IT platform is very useful when it comes to automate and enhance the OIGP creation, however, one of its limitations consists in the integration of economic models. Although some models are already integrated within the platform, some are still missing, which restricts the specialists from fully understanding the economic viability of their proposed projects.

Economic models are an essential part to understand the feasibility of the land use proposals ([Direção Geral do Território 2023](#)), since they provide the ability to evaluate if a given scenario will generate the income necessary to surpass the initial investment to reorganize a determined area. The values returned by the economic models integrated will give the necessary insights to guide decisions that balance both economic and ecological resilience of the projects developed.

Therefore, this study aims to address this gap in the platform. Models for key land uses such as maritime pine, Eucalyptus, Cork Oak and Olive Trees will be incorporated, as well as a study for Solar Panels' installation. These models will provide detailed information regarding the Net Present Value, Equivalent Annual Annuity, Total Costs and Total Profit, helping them to be more informed when analyzing the viability of their developed projects.

4. sIMfLOR Platform

This chapter introduces sIMfLOR, that integrates diverse simulators for the principal forestry species in Portugal and aims to facilitate the use of growth models by its users. It allows to

manage data inputs, running and visualizing outputs. This chapter is divided into two sections, providing a detailed description of the StandsSIM and the SUBER simulators.

4.1 StandsSIM

In the following subsections the StandsSIM simulator will be introduced. The first section will give an overview, while the subsequent ones will describe both the inputs and outputs given. Finally, the last section describes some improvements made to the simulator during this study.

4.1.1 StandsSIM Overview

The StandsSIM is a Management Driven Forest simulator developed to model and predict forest growth dynamics for Portugal's primary wood-producing species: eucalyptus (*Eucalyptus globulus*) and maritime pine (*Pinus pinaster* Aiton.). Designed to address challenges like deforestation, reduced wood production, and compromised carbon sequestration exacerbated by climate change and wildfires in the Mediterranean region, StandsSIM provides a long-term simulation framework tailored to Portuguese forest landscapes (Barreiro et al. 2016); Simflor Platform 2024). Its advanced growth models allow for simulations at both the individual-tree and stand levels, offering flexibility for even-aged and uneven-aged stands. By incorporating theoretical models and customizable silvicultural operations — such as harvesting, thinning, and planting — StandsSIM ensures adaptability for diverse forest management scenarios.

StandsSIM's unique advantage lies in its integration of climate dynamics, wildfires risks, and economic variables into forest simulations, filling the gaps left by earlier simulators. Users can tailor parameters like basal area targets, thinning intensity, and planting densities to meet specific goals while evaluating financial metrics, such as operation costs and production receipts (Barreiro et al. 2016). These features empower landowners and forest managers to make informed decisions. By combining cutting-edge models, StandsSIM is an indispensable resource for addressing the evolving challenges of forest management in Portugal.

4.1.2 Inputs

The StandsSIM requires a variety of inputs related to the forest management approaches, costs of operations, prices and site characteristics. Moreover, data on the climate of a specific country, region or even management unit is integrated, tailoring the predictions to each specific land.

Firstly, data on the stands' characteristics is received for new and existing stands. For both, information on the species – if the simulation is for maritime pine or eucalyptus –, age of the stand in years, number of trees planted per hectare, if the stand is even- or uneven-aged, and the time horizon planning, is gathered. For the specific case of existing stands simulations, there is a need for additional data related to tree measurements, such as height and diameter. At this stage, the user can also specify the beat-up rate, representing the percentage of trees planted that are expected to die, making it possible for the simulator to account for the mortality rate.

Moreover, data on silvicultural operations is gathered. This accounts for all silvicultural practices taking place in the culture's lifetime. There is a wide variety of operations for the user to choose, from land preparation, planting, cleaning, thinning, final harvesting, debarking and shoot selection. Thinning operations involve selectively cutting individual trees of a stand while the final harvesting is the last cut when trees reach commercial maturity ([Mendes et al. 2017](#)), where fully-grown trees are collected. Both operations generate income ([Centro Pinus 2016](#)). Although thinning occurs more than once in the life cycle of maritime pine, it generates less revenue compared to the final cut, as trees are smaller. Moreover, the simulator operates under the constraint that shoot selection must take place in the same ordinary year across all rotations. For the eucalyptus, information on the duration of each rotation cycle is also necessary.

Furthermore, growth conditions are mandatory inputs for the simulator to predict the trees' growth over time. To measure the productivity capacity of a specific site, the simulator receives the site index. This forestry measurement is expressed as the expected height of dominant trees,

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based on previous plantations in that land, and at a specific reference age that depends on the species and region ([ICNF 2021](#)). The height of the tallest or most vigorous trees reflects the quality of the growing conditions, making the predictions for the tree growth more accurate.

For accurate financial predictions, it is important to gather economic inputs, such as costs and revenues. The costs of each silvicultural operation and corresponding unit –tree, kilometer or hectare –, costs on wages and products such as seeds, pesticides, and fertilizers are necessary to calculate total cash outflows. For the revenue's calculation, it is necessary to input wood and biomass prices. Lastly, climate data such as number of rainy days per year, precipitation, average temperature and frost days is gathered to simulate the growth pattern of each species.

By integrating all this information, the simulator generates highly accurate and customized predictions for each forest management unit. This high volume of inputs ensures a realistic simulation, providing a robust tool for informed decision-making in forestry planning.

4.1.3 Outputs

With the inputs presented in [Section 4.1.2](#), the simulator generates some outputs, in the form of comma separated files, with the growth and financial predictions for each site index inputted.

The first output file provides information about the number of trees alive throughout the species' lifespan and their corresponding diameters. As such, for each site index and year, the simulator predicts the number of alive trees and distributes them across different diameter ranges. An overview of this file is presented in the [Appendix IV Section](#), in [Figure IV.2](#).

Moreover, the simulator creates another output file with financial predictions. For each site index, the simulator calculates the Net Present Value (NPV) and Equivalent Annual Annuity (EAA) for discount rates of 3%, 4% and 5%, allowing users to select the rate that aligns with their desired rate of return. The NPV assesses the project's profitability by calculating the present value of future cash flows and comparing them to the initial investment ([Brealey et al.](#)

2020). The EAA translates the NPV value into a constant annual cash flow, helping to access the evaluation of projects with different time horizons (Brealey et al. 2020). A visual of this file is depicted in Figure IV.3 present in the Appendix IV Section.

Lastly, the final output file combines all calculations from the simulator. For each year and site index, the simulator computes over 50 indicators. Starting with the final cut, thinning and debarking operations, the file marks the year in which these were performed. This is of extreme importance because, maritime pine is subject to Wilson Factor criteria.

Wilson's Factor consists of a relative measure of stand density, which evaluates the appropriate number of trees per hectare in a stand, as a function of the dominant tree height, being a key measure in guiding thinning operations. The logic behind the Wilson Factor is that larger trees (with greater heights or diameters) require more space, resulting in fewer trees per hectare for the same stand density. In contrast, smaller trees can support a higher density.

Thinning is an operation performed to optimize growth conditions. If the number of trees per hectare in a stand is already below the threshold determined by the chosen Wilson Factor, no thinning is applied, ensuring that the stand is not under the deserved number of trees per hectare. The site index has a certain influence, as trees in higher site indexes achieve greater heights and diameters than those at lower site indexes, at a faster rate. This rapid growth means that trees occupy more space earlier in their development, reaching thresholds of competition and crowding sooner, therefore requiring thinning operations to occur sooner. Conversely, trees that grow in less productive soils achieve smaller height and diameter, taking longer to reach the thresholds associated with competition. This leads to the delay of thinning operations.

For the maritime pine case, the simulator works under these explanations. Even if a thinning operation is prescribed by the user, the simulator will only execute it if the conditions mentioned above are fulfilled. Specifically, for thinning operations, the simulator checks if the tree density

is sufficient, given the site index conditions applied, to proceed with the operation. As such, if a thinning operation is scheduled for a year when the stand density falls below the required threshold, the operation is skipped and a 0 is recorded for that year in the output file. This distinction is very important since it ensures the simulation is realistic and intelligent, avoiding operations that violate the imposed requirements.

Additionally, the file also provides the expected tree's dominant height for each year, along with the number of trees that are expected to be alive or dead. Other calculated indicators include the basal area, wood volume with and without bark, total wood volume produced and cut, and biomass volume – distinguishing between branches, leaves, resin and more. Lastly, the file also includes financial data, detailing the inflows from wood and biomass sale, and outflows related to management schedules, assortments and labor costs. The revenues generated by biomass are also recorded, allowing the simulator to calculate the Net Present Value (NPV) for each year, its cumulative, and the Equivalent Annual Annuity (EAA) of the project.

This final output file is the most important to analyze, as it consolidates all information in one place, shown by [Figure IV.4](#) in the [Appendix IV Section](#). As such, for further evaluations, it should be the main focus, as it can reveal essential insights and trends.

4.1.4 StandsSIM Improvements

The StandsSIM simulator requires a significant amount of information. As a result, consulting forestry specialists in Mação became critical to determine fixed parameters applicable across the region. For example, it was clarified that Mação only sells wood in eucalyptus plantations, while biomass is also sold for maritime pine stands. Additionally, the costs associated with land preparation, plantation, maintenance and harvesting are uniform across all AIGPs. This allowed these parameters to be treated as fixed inputs for the model. To obtain these values, consultations with experts such as [Margarida Tomé](#), professor at [Instituto Superior de](#)

Agronomia, and *António Louro*, president of *AZR* and *Aflomação*, were conducted. By these, practiced prices in the municipality, the typical planning horizons for maritime pine and eucalyptus stands, and other critical metrics were gathered. These values and operations are explained in Sections 5.7.1 and 6.7.1 of the maritime pine and eucalyptus chapters, respectively.

One of the most important inputs for the simulator is the site index, as previously mentioned. Unfortunately, no specific data was available regarding site indexes for maritime pine and eucalyptus lands in *Mação*. To address this issue, data from the *Inventário Florestal Nacional* was used, covering parcels in *Mação* and nearby municipalities (*Proença-a-Nova*, *Sertã*, *Vila de Rei*, *Sardoal*, *Abrantes*, *Gavião*, *Nisa*, and *Vila-Velha de Ródão*). Based on this information, three possible site index scenarios were calculated: low (*Mação 5*), medium (*Mação med*), and high (*Mação 95*). These site indexes - 15.44, 20.69, and 25.86 for low, medium, and high productivity levels, respectively - enabled simulations to be evaluated under different growth scenarios. Since the productivity of maritime pine and eucalyptus soils is similar in *Mação*, the same site indexes were applied for both species in the simulations.

However, working with the *StandsSIM* simulator posed significant challenges during this thesis. The simulator had to be replaced, updated and improved eight times due to errors and inconsistencies identified throughout the research process. These repeated changes required constant adaptation and recalibration of the models, which added complexity to the analysis. Despite these difficulties, the iterative process led to more accurate simulations and a deeper understanding of the proposed landscape management strategies.

4.2 SUBER

This section introduces *SUBER*, its inputs, simulation process and outputs.

4.2.1 SUBER Overview

The SUBER simulator was specifically developed for the management of cork oak stands in Portugal. By providing simulations for cork oak plantations, it enables analysis of cork production, stand growth and economic viability along the tree's lifecycle.

This simulator has various improved versions, the most recent one the SUBER 5.0. This can calculate cork production independently of the tree's age, allowing more flexible simulations for different management scenarios. Additionally, SUBER 5.0 integrates a site quality index that considers the management practices, soil and climatic variables. The index assesses the productivity potential of a stand to plan the strategies that will maximize the cork production and economic returns. Another distinctive feature of SUBER 5.0 is its classification as an individual-tree and distance-independent model. This approach simplifies calculations by excluding spatial competition indices, making it applicable across various management scenarios while maintaining robust predictions for tree growth, cork production, and stand dynamics. This version also simulates new cork oak stands without requiring prior forest data, expanding the model's usability to areas where historical data is unavailable.

To improve its utility, the model incorporates a graphical user interface within the sIMfLOR platform, enabling visualization of simulation results. Overall, SUBER 5.0 represents a comprehensive tool that allows the simulation of long-term cork oak stands and its evolution, allowing to better understand the impact of the management practices.

4.2.2 Inputs

SUBER 5.0 requires a detailed and structured set of inputs to guarantee accurate predictions. These inputs are the foundations for predicting growth and economic parameters over time and can be distinguished between inventory and economic data. The inventory data contains variables such as tree identification, height, cork thickness, and harvesting height collected

during forest inventories. The model also incorporates specific parameters for cork harvesting, including the minimum age for the first stripping, coefficients for cork removal, and whether subsequent harvests will increase the harvesting height. This data must follow strict validation rules on cork age, harvesting height and the number of cork layers removed, ensuring it aligns with structural and legal requirements of cork oak management. This validation is important as it helps to avoid errors that could compromise the accuracy of the simulations.

Regarding the economic inputs, it includes information on labor costs, machinery, consumables and management operations, as well as revenues derived from cork and wood products. To calculate revenue, cork and wood, prices are necessary and can be differentiated by cork type, such as virgin or "amadia" cork. Cork price ranges can also be defined by five caliber classes (e.g., <18mm, 18–23mm, 23–27mm, 27–41mm, 41–90mm) and three quality levels (e.g., grades 3, 4, and 5), creating up to 15 combinations that reflect real market conditions. The discount rate used to calculate the NPV and EAA is 5% by default but can also be adjusted.

Lastly, the stand's operational plan is received as input. Users can specify operations for regular or irregular stands, reflecting the diverse realities of cork oak stands. Finalizing input configuration process, users can save the inputs in formats compatible with SIMfLOR's platform, enabling seamless integration and its future reuse for multiple simulations.

4.2.3 Simulation

There are two types of simulations: one for newly established stands and another for existing forests, allowing users to simulate different scenarios, depending on available data.

For new established stands, as there are no measurements, the model uses data collected from forest inventory plots, allowing for a precise analysis of growth. Users can choose between simulating each plot individually, enabling highly specific projections, or aggregating data to represent a larger stand, used when data is not available or when the objective is a general

overview of forest dynamics. For the specific case of already existing forest, users must add information on the number of branches, total height, cork caliber, and cork quality. If tree measurements are not available, the model estimates them from existing data.

Regardless of the approach, the simulations executed and its results are accessible, enabling the analysis of outputs such as production trends, biomass growth, and cork quality over time.

4.2.4 Outputs

Outputs are tailored to provide insights into tree and stand level. At the individual tree level, the model analyzes variables like height, basal area, and diameter growth.

At stand level, the outputs analyze general trends of the stand, such as the basal area with and without cork, the density of trees per hectare, and canopy coverage. This perspective provides a better understanding of the stand's overall growth trajectory. Cumulative to that, the data on biomass components, including wood, branches, leaves and roots, show the total productive capacity of the stand. The metrics on the weight and quality of the cork harvested (virgin and “amadia”) provide insights into economic outputs over multiple harvest cycles.

The outputs also record the metrics before and after interventions, such as cork harvesting or thinning, and help to understand the changes in growth dynamics and the impact of the interventions. The diameter class evolution and carbon stock are other metrics present in the outputs. The diameter class evolution demonstrates how trees progress through various size categories, while the carbon stock reflects the stand's role in carbon sequestration.

The SUBER simulator also integrates visualization tools. The generated graphics and charts allow for easier interpretation of complex datasets and aim to help strategic decision-making. By analyzing detailed quantitative data with environmental and operational considerations, the outputs allow forest managers, researchers, and policymakers to make informed decisions that balance economic returns with ecological awareness on the cork oak.

5. The case of Maritime Pine

5.1 Maritime Pine in Portugal

In Portugal, the pine forests have historically played an important role in the country's forest sector. However, these ecosystems have experienced significant reductions in area due to factors like wildfires, pest infestations and diseases. Between 1995 and 2015, the area of maritime pine forest has shown a decrease of around 264,000 hectares, although, the rate of reduction slowed significantly between 2010 and 2015 (ICNF 2019). Nowadays, maritime pine is the third most common forest species in Portugal, covering around 22% of the country's total forest area, which corresponds to around 1 million hectares (ICNF 2019).

This species has been in Portugal for over 33,000 years (Figueiral 1995) and is distributed across the Northern and Central regions, covering areas from Tejo and Sado basins up to Minho. Additionally, it is found in inland areas of the Center and South, specifically in Penamacor, Idanha-a-Nova, Serra Mamede and Santo Aleixo da Restauração (Autoridade Florestal Nacional 2012), at hypsometric levels ranging from 700 and 900 meters (Oliveira et al. 2000).

5.2 Maritime Pine characteristics

Maritime pine is very adaptable, resistant to prolonged dry periods, cold and moderate climate conditions, managing to grow and develop in unfavorable environments. However, this forest species is light-demanding, unable to tolerate shade due to its leaf structure (Oliveira 1999). This tree shows preference for siliceous and sandy soils, with depths up to 30 to 60 cm (Florestas 2023), where its roots can grow freely. *Pinus Pinaster Aiton.* has a better development in areas where the medium temperatures round the 11°C and 15°C (Centro Pinus 2016), with annual precipitation between 550 mm and 1200 mm (Centro Pinus 2016). However, due to its resilient characteristics, it was widely used for the afforestation of coastal dunes and

mountainous wastelands. It played a key role in early reforestation initiatives in Continental Portugal, as well as in the autonomous regions, as it allowed to plant forests on steep terrain, serving as protection against erosion and floods ([Florestas 2023](#)).

This species lives for 200 years in optimal conditions, however, signs of crown weakening and reddening of the bark indicate aging, and it starts around 80 to 90 years ([Centro Pinus 2015](#)).

Maritime pine has a big relevance to Portugal when it comes to economy, since practically all the tree's parts can be commercialized. Although the main product is wood, resin is a product that generates annual revenue, as well as biomass that consists of various components of this forest species ([Gonçalves et al. 2020](#)), such as its bark, needles, branches and leaves.

5.3 Growing Cycle

The typical growing model of maritime pine consists of plantation, cleaning, and maintenance activities, and different phases of growth. The plantation involves a recommended density of 1,250 to 1,670 trees per hectare and a minimum distance of 3 meters between rows is required ([Oliveira et al. 2000](#)). According to [Centro Pinus](#), *Pinus Pinaster Aiton.* growth is divided into 5 different phases: Nascedio – Seedling Stage, Novedio – Young Growth Stage, Bastio – Thicket Stage, Fustadio – Pole Stage, and Alto Fuste – Mature Tree Stage. These stages of growth characterize the tree based on its dimensions, as presented in Table 5.1 ([Centro Pinus 2018](#)), where hdom/ddom represent the average heights and diameters of dominant trees.

	nascedio	novedio	bastio	fustadio	alto fuste
ddom(cm)	-	0-10	10-20	20-30	30-50
hdom(m)	0,3-1,3	1,3-8	8-15	15-18	18-20

Table 5.1: Diameter and height variations in maritime pine ([Matias, 2023](#))

The planting period, Nascedio, varies between areas. For areas with prolonged summer, such as Minho or Douro, planting should occur from November to May, and, in more Central and Southern regions, planting should take place from November to March ([Oliveira et al. 2000](#)).

When it comes to cleaning, it consists of removing the lowest quality, dead and diseased, or non-dominant trees and is recommended that, by the age of 10, the stands' density reduces to 1000 or 1200 trees per hectare (Oliveira et al. 2000). Thinning should occur first around 15 to 20 years after planting, and with intervals of 5 to 10 years. In this process, 20% to 30% of the stand's trees should be removed (Oliveira et al. 2000), with exception to the first, that should be denser than the others, where 20% to 40% of the trees are cut (Matias 2023).

The final cut is the last process that occurs in a stand of maritime pine and usually 300 to 500 trees are removed from the stand (Oliveira et al. 2000). An image that illustrates the growing cycle of maritime pine can be found in the Appendix V.1 Section.

5.4 Related Work and State of the Art

Maritime pine is a resinous species highly valued for its fire resistance. According to Fernandes et al. (2005), this species has evolutionary features that result from adaptations to fire: resistance, evidenced by its thick bark, that protects the tree from low-intensity fires, and evasion, through thermally induced cone dehiscence, enabling the tree to reproduce after exposure to high-severity fires. These characteristics made maritime pine a key species for reforestation in vulnerable regions, including Mação, one of the most affected areas in Portugal.

Several projects have been developed to study the ecological resilience and economic viability of maritime pine. Research by Gómez-García et al. (2015) highlighted the importance of using height-diameter models to enhance forest management practices, since accurate tree height predictions combined with diameter, and other specific stand variables, have proven essential for monitoring forest growth and optimizing yield projections.

Moreover, Alegria's (2004) study emphasized the importance of growth and production models to forest management, since these allow to predict future production and explore different forest intervention options. PBIRROL, which consist of growth and yield models tailored to the

irregular stands of maritime pine in the Oleiros region developed by Alegria (2004), can be applied to similar forest systems, like Mação's region. This helps to predict the future productivity of future replanted forests, since individual growth of the trees can be studied.

The work of Alegria (2007) and Tomé et al. (2007) also contributes to this by providing equations for estimating total and mercantile wood volume to commercialize. While Alegria's (2007) equations are more specific to regions like Castelo Branco, Tomé et al.'s (2007) ones can be used across the country, making them more useful for predicting the volume of wood available for commercialization in Mação. These equations are crucial when it comes to calculating potential economic returns from the reordering of territory with maritime pine.

In addition, Ogana et al. (2020) presented a new height-diameter model that has been developed to both *Pinus Pinaster* and *Pinus radiata* (Monterey Pine) in Spain. This model consists of a nonlinear mixed-effects technique that provides predictions of tree's height from diameter measurements, yielding a Root Mean Square Error (RMSE) of 0.906 for *Pinus Pinaster*.

A similar study in Northeast Portugal by Msaouak (2016) also shows the potential of using mixed models when it comes to improving the predictive performance. Applying height-diameter equations can help estimate tree volume, competition indices and assessing the stand dynamics in general, crucial to optimize wood production, and, consequently, the potential economic return that Mação can have. Msaouak (2016) thesis also mentions that this resinous can thrive in fire-affected areas, emphasizing its ideal characteristics for reordering forests. Combining the potential of maritime pine to thrive after wildfires and by using the mixed models mentioned, it is possible to assess the long-term potential of this species. This way, wood production can be maximized, offering some financial return to Mação's municipality.

StandsSIM, a forest simulator developed by Barreiro et al. (2016), incorporates up-to-date models sensitive to climate change scenarios, and allows users to project forest growth,

considering a range of management prescriptions. The analysis made by this existing simulator helps to analyze the economic viability of reordering territory in areas affected by fires with maritime pine. The usage of this simulator can help users understand which management approach can yield a higher Net Present Value as well as higher wood production over time, while keeping the production costs affordable for the municipality. Also, it helps in understanding which species is more economically feasible compared to others.

The studies and models presented in this section represent some fundamental tools to evaluate the ecological and financial viability of reordering Mação's forest. From height-diameter models to advanced growth simulators, like StandsSIM, these tools enable accurate predictions of growth, yield, and financial returns. Bridging these models in the LAND IT platform, this thesis aims to create a comprehensive decision-making framework to support sustainable and economically viable reforestation projects in fire-affected areas.

5.5 Methodology and Approach

In this part, the objective was to build a growth and economic model for maritime pine that can be integrated into the LAND IT platform. The model aimed to calculate the expected profit from wood, resin and biomass, over the entire life cycle of the species, using users' information about their maritime pine stands. Before developing the model, it was necessary to review relevant literature to incorporate the most accurate growth functions into the model.

Unlike species treated collectively as a stand, maritime pine trees are modeled individually, with the calculations performed on a tree-by-tree basis. This approach allows for more detailed predictions, as it accounts for individual variations in tree height, diameter, and growth patterns.

In this first approach, the decision was to start designing a model that calculates wood, biomass, and resin's volume as well as the associated profit for each tree, based on its specific attributes of height and diameter. These individual calculations would then be aggregated to estimate

these values for the entire stand. Recognizing that users may only have information regarding their stand's age, it became essential to either develop or find functions capable of estimating tree height and diameter as a function of the maritime pine's stand' age.

One challenge encountered was the lack of reliable data that links height, diameter and age, crucial for building a predictive model. In scenarios where users may only have information on the age of their stand, the inexistence of equations that relate these variables made the accurate estimation challenging. Height-Diameter models, such as the ones mentioned by Gómez-García et al. (2015) or developed by Alegria (2004) to estimate *Pinus Pinaster Aiton.* growth and production, although useful and widely applied in Portugal, were not age dependent. Instead, they rely on other variables, such as basal area – cross-sectional area of tree trunks at 1.3 meters above ground – and dominant height – height of the 100 tallest trees per hectare in a stand – which are, similarly, very difficult to estimate in the absence of specific data.

Despite extensive research, no models were found that estimated tree height and diameter based on age or other variables that could be estimated. Without equations that module the evolution of the tree's height and diameter over time, it becomes difficult to perform reliable calculations. Users would need to know their stand's average height and diameter in each process – thinning, final harvesting, resin and biomass extraction – to calculate the net value precisely. Even with this information, the results of the predictive model would likely remain inaccurate, since the calculations would have to be performed in a collective approach, while stands of this species are managed on an individual-tree basis in practice.

After careful evaluation and consulting with forestry experts, it became clear that continuing with the development of the growth and economic model was not feasible, especially, given the existence of well-established simulators such as StandsSIM. As a result, instead of duplicating their functionality, it was opted to integrate these simulators into our system.

The focus began to build an API that integrates an established simulator, StandsSIM. This change allowed the project to use StandsSIM existing empirical models and larger database, more suitable for generating accurate predictions without requiring extensive additional data.

To pursue the API development, some data regarding fixed values and management approaches that were commonly applied in Mação was gathered. Once all the data was collected, the API development started. The management of the stand and the horizon planning were set as input variables, allowing the model to adapt to changing management strategies over time. The biomass and wood prices were, as well, left as input variables due to their dynamic nature.

After the API was developed, testing was conducted using the data that was gathered from Mação. The results were analyzed in terms of economic viability for new maritime pine stands, and sensitivity analysis was performed to assess whether the current management strategies used in the region are optimized for maximizing profitability.

5.6 Developed Models

The literature presented in [Section 5.4](#) enabled the creation of a growth and economic model in Python. This model aimed to simulate the lifecycle revenue generated from wood, resin and biomass, using user-provided data. The details of this design, as well as the equations used to perform it, are presented in the [Appendix V.2 Section](#).

Due to the already mentioned reasons in [Section 5.5](#), the approach changed, so, this section will focus on the integration of StandsSIM simulator into LAND IT platform. The development of the API followed three main stages: inputs, simulations and outputs.

5.6.1 Inputs

The first stage focused on structuring the necessary user inputs for the simulation. To structure and analyze the parameters provided by the users, a class was created, ensuring that all values provided followed the data type restrictions implemented.

The main input variables included final cut age, which defines the planning horizon of the simulation, number of hectares, management schedule and wood and biomass price. The management schedule accounts for key information to run the simulator, such as the periodicity of harvesting operations, the beat-up percentage and the number of trees planted per hectare. Also, two different wood prices were required since Mação makes a distinction between the selling value of wood that is collected for chipping actions and to sawmilling actions.

5.6.2 Simulation

Once the input structure was developed, it was necessary to implement functions that automatically modify and update the input files, inherent to StandsSIM, with information provided by the user. A group of functions was developed to customize the management schedule - based on a list of predefined operations, specifically mentioned by Mação's forest experts - the timing for key operations like harvesting and thinning, the wood and biomass practiced prices and total number of hectares being simulated.

5.6.3 Outputs

The outputs that are being given to the user include total costs and receipts, Net Present Value (NPV), Equivalent Annual Annuity (EAA), total wood and biomass revenues.

In addition, a visualization interface was integrated into the outputs, so that users could analyze the evolution of some parameters over time. The created visualizations available include the changes over the simulation years for dominant height, number of trees, basal area, wood volume, biomass weight, quadratic mean diameter, NPV and EAA.

5.7 Results' Analysis

5.7.1 Assessing the profitability of the proposed management approach of Mação

To evaluate the profitability of the proposed management approach of Mação, a simulation was conducted based on the information provided. Using data from the ICNF's 22 document, it was possible to understand that the region has a horizon plan of 46 years, with harvest operations occurring at regular intervals of 10 years, starting in year 17. Since the simulator needs a threshold on the Wilson Factor metric, a value of 0.25 was indicated.

In addition, maintenance operations – such as regular vegetation control, plantation, soil preparation and fertilization – are routinely performed in the territory. Since plantation operations are conducted, Mação added the information that 1,470 trees are planted per hectare, and that it is expected that beat-up percentage has a value of around 15%. By combining this information with details about the commonly practiced prices applied in Mação, it was possible to create a schedule of operations and input accurate pricing data for the simulation.

5.7.2 Output and analysis of the results

Table 5.2 presents the results obtained for the three productivity scenarios.

Scenario	Site Index	Total Cash Inflows (€)	Total Cash Outflows (€)	NPV (€)	EAA (€)	Total Wood Revenues (€)	Total Biomass Revenues (€)
Mação 5	15.44	15354.5	1605.4	1181.0	56.5	14461.5	893.0
Mação med	20.69	28359.7	1605.4	4123.2	197.4	27693.5	666.2
Mação 95	25.86	43884.5	1605.4	8449.1	404.6	43188.9	695.6

Table 5.2: Simulation Results for Mações' management approach for three site indexes

As expected, higher site indexes result in higher cash inflows, wood revenues and greater NPV and EAA, showing the influence of land productivity levels on the overall financial outcomes. Notably, total costs have remained unchanged in all scenarios, with a value of €1,605.4, indicating that operational costs do not depend on productivity levels.

An observation from Table 5.2 is the decrease in biomass revenues with the increasing site index. Contrary to wood revenues, biomass revenues decline as productivity increases. In lower productivity scenarios, like *Mação 5*, trees often do not reach heights or diameters required for viable wood commercialization, resulting in higher biomass revenues, explaining the €893 obtained. Intermediate productivity scenario yields the lowest biomass revenue, €666.2, as more trees meet wood standards. High productivity scenarios, like *Mação 95*, balance faster growth with increased residue collection throughout the time horizon planning, reflecting the €695.6 revenues.

Wood revenues increase with productivity. In *Mação 5*, lower tree density and delayed thinning operations limit wood revenue, justifying the lowest value of €14,461.5, since revenues from wood are solely obtained in years 37 and 46 (year in which the final cut is performed). The medium scenario includes an additional thinning operation, in year 27, reflecting higher wood revenues. Finally, *Mação 95* generates the highest wood revenues, €43,188.9, due to the execution of all scheduled thinning operations.

Consequently, *Mação 95* scenario achieves the highest NPV (€43,884.5) and EAA (€404.6), while *Mação 5* shows the lowest values since fewer income operations are performed. These results reinforce the importance of selecting high-quality sites to plant maritime pine stands, as well as the imprudence of performing three thinning operations in soils with site indexes similar to *Mação 5* and *Mação med*. For a better understanding of changes that occur throughout the stands' lifecycle, some of the most relevant charts will be introduced.

The dominant height gives important information on site productivity, as dominant trees are the least affected by competition and reflect the quality of the growing environment. Figure 5.1 shows the behavior of this parameter through the 46 years of the stand. It is easy to see that

higher site indexes achieve faster growth rates and higher maximum heights. *Maçã 95* has the highest growth rate and maximum height, while *Maçã 5* has the lowest in both.

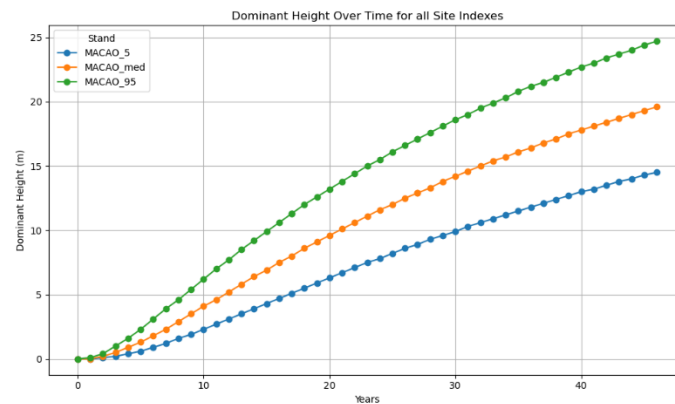


Figure 5.1: Dominant Height over time for three site indexes

Figures 5.2, 5.3 and 5.4 show the evolution of tree density over time. In *Maçã 5*, only one thinning occurs, – visible by the only decrease in the chart – leading to minimal reductions in tree density. Figure 5.3, representing the medium scenario, two decreases are shown, in years 27 and 37, where thinning occurs, and, finally, Figure 5.4, the highest and only productivity scenario that had the required number of trees to perform the three thinning scheduled, resulting in a lower density of trees. This is a result of the principal objective being the production of high-quality wood coming from trees with larger diameters. In higher productivity stands, the wood has higher economic value, and is therefore harvested and sold more extensively, whereas this is not the case in lower productivity stands.

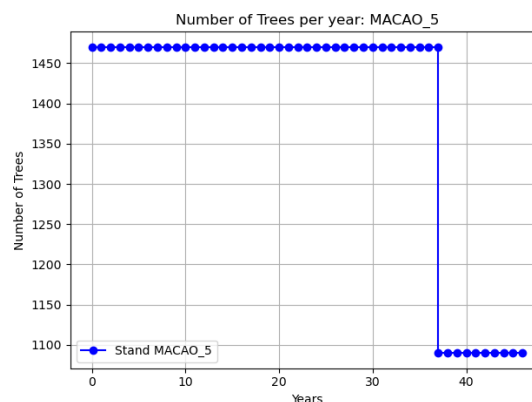


Figure 5.2: Number of trees over time for *Maçã 5*

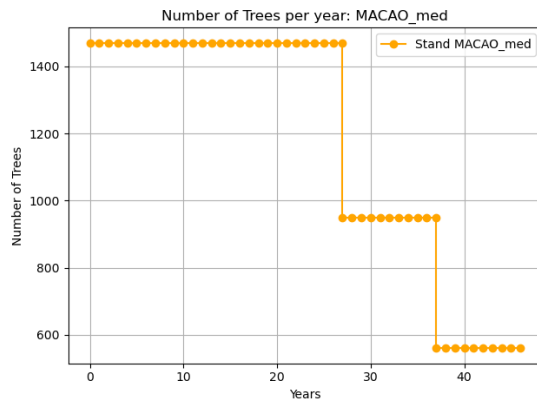


Figure 5.3: Number of trees over time for Mação med

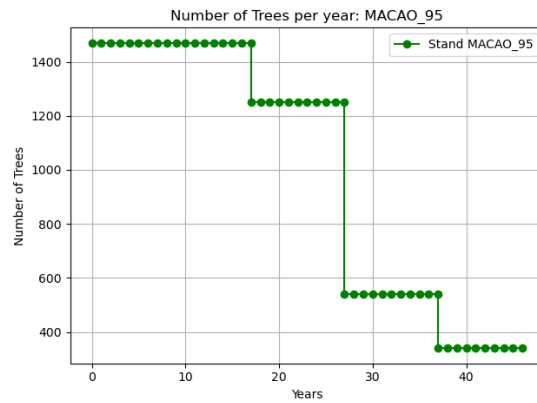


Figure 5.4: Number of trees over time for Mação 95

Graphs of wood volume and basal area evolution can be seen in the [Appendix V.3 Section](#).

Lastly, [Figure 5.5](#) shows the trends in cumulative NPV across site indexes. *Mação 5*'s cumulative NPV remains negative for most of the planning period, only reaching positive values at the final cut age – the last point of the chart. *Mação med* achieves positive values at the second thinning, at year 37. *Mação 95*, turns positive earlier, at the second thinning in year 27, explained by both the number of harvesting operations performed, and the economically viable wood that is collected in each scenario. Since both NPV and EAA follow the same trends of cumulative NPV, a deeper analysis will be done regarding only this plot, others can be seen in the [Appendix V.3 Section](#).

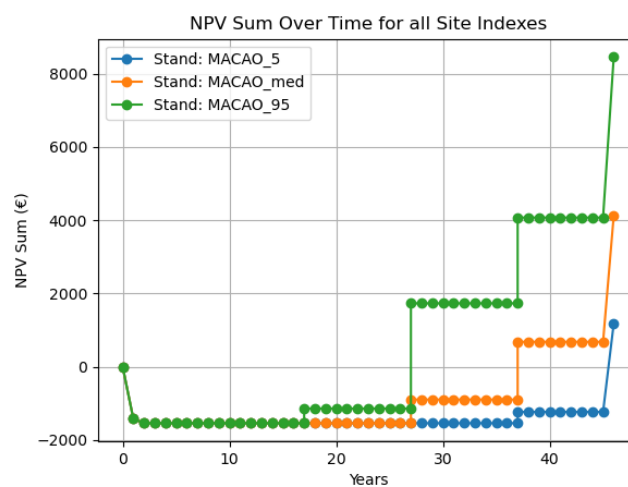


Figure 5.5: Cumulative NPV over time for three site indexes

5.8 Sensitivity Analysis

To assess the impact of the input parameters and highlight opportunities for maximizing profit, it is crucial to perform a sensitivity analysis, so that users can identify which factors have the greatest potential to be improved. To provide *Mação* with the best and most informed advice regarding their management approach, both univariate and multivariate analysis were conducted to change the following parameters: Number of trees per hectare, Beat-up percentage, Final cut age, First harvesting operation year and regularity.

5.8.1 Univariate Analysis

In this analysis, each parameter that seemed probable of influencing the profit outcome was isolated. Between the selected parameters, a range of acceptable values was tested to determine their individual impact on the NPV. The outputs that resulted from each analysis were compared to *Mação*'s base values, enabling the identification of the ones that may be able to enhance profitability. The charts used to perform this analysis were designed in Tableau Desktop.

5.8.1.1 Tree Density per hectare

An analysis, performed to assess the ideal tree density to maximize profit was conducted, using a range of values among 1,250 and 1,670, incremented by 10, as recommended by *Centro Pinus*.

A bar chart was designed for each productivity scenario. In [Figure 5.6](#) we can observe that *Mação 5* shows the lowest NPV values, while *Mação 95* has the highest ones. The NPV for 1,470 trees per hectare, representing the current number used in *Mação*, is marked in each chart.

The maximum NPV is highlighted as well and, in the case of *Mação 5*, the highest NPV, €1,252, occurs with 1,590 trees per hectare. In *Mação med* and *Mação 95* the highest NPVs were €4,502 and €8,952, with 1,670 and 1,660 trees per hectare, respectively.

As noticed, in none of the scenarios, the current tree density aligns with the value that maximizes the NPV, however, and as visible, the variation between bar sizes, is minimal across all scenarios. This indicates that, although the NPV increases, the rise in question may not be significant to justify the change in the current practice. Percentage differences between the NPV of the current and optimal tree densities can be seen in [Table V.1](#) of the [Appendix V.4 Section](#).

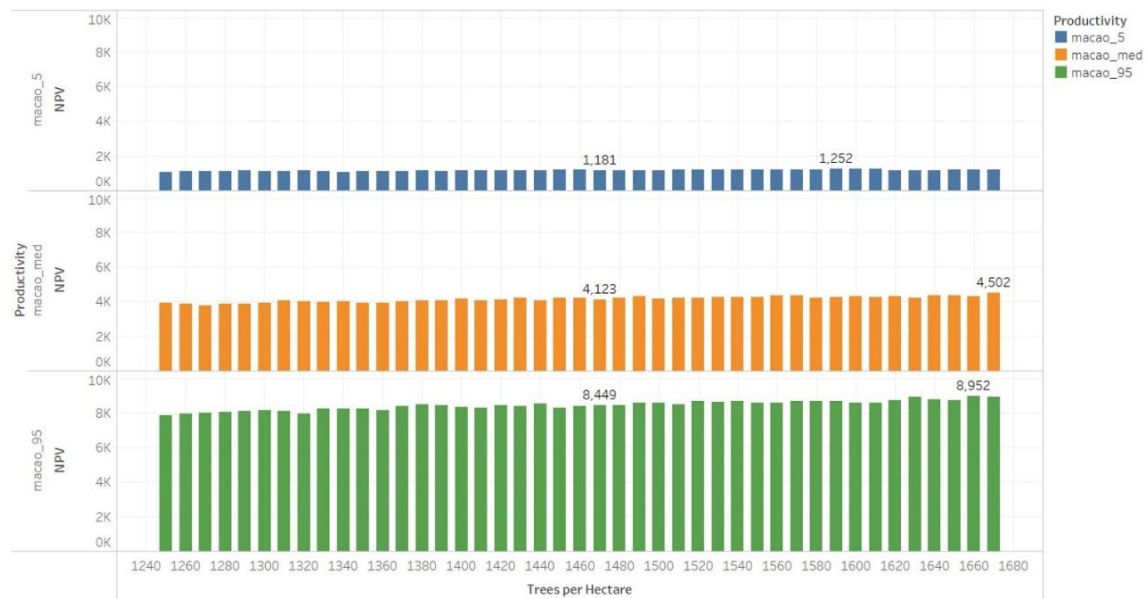


Figure 5.6: Sensitivity Analysis of NPV of different Trees per hectare, for all three scenarios

5.8.1.2 Beat-up Percentage

The beat-up percentage refers to the proportion of the stand that requires replanting due to tree mortality ([Produtores Florestais 2024](#)). Since this process involves replacing trees that died, it is logical to aim for the lowest percentage possible, so additional costs associated are minimal. A sensitivity analysis, ranging from 5% to 25 %, with 5% increments, is shown in [Figure 5.7](#).

It is visible in [Figure 5.7](#) that, across all productivity scenarios, when the beat-up percentage increases, the NPV tends to decrease, implying that a negative correlation between these variables exists. For instance, in *Mação 5* scenario, the NPV decreases significantly by 23.97% as the beat-up percentage rises from 5% to 25%. A smaller decline is seen in *Mação med* and

Mação 95, that only diminish 7.51% and 3.74%, respectively. More details regarding these differences in NPV can be seen in [Table V.2](#), in the [Appendix V.4 Section](#).

These results show the importance of maintaining high-quality soil, especially in lower productivity areas, to minimize the beat-up percentage and enhance profitability.

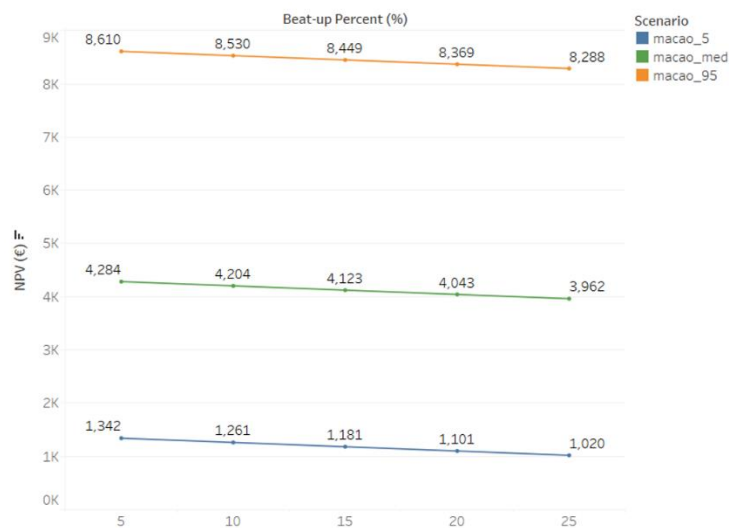


Figure 5.7: Sensitivity Analysis of NPV with different Beat-up percentages

5.8.1.3 Final Cut Age

In regions regularly affected by fires, trees are usually harvested earlier, at 35 years, as a strategy to diminish fire risk. However, under optimal conditions, the ideal age is 50 years. A sensitivity analysis was conducted using EAA instead of NPV, given the varying project time horizons. The results in [Figure 5.8](#) show that the final cut age applied by *Mação*, set at 46 years, is already optimal for the schedule implemented, suggesting no necessary adjustments in this input.

Moreover, by analyzing [Figure 5.8](#), it is possible to assess the impact of cutting stands earlier than scheduled, a practiced implemented by many Portuguese regions. In the case of lower productive soils, this approach can result in negative annual profits, as trees are not able to reach their maximum potential height and diameter.

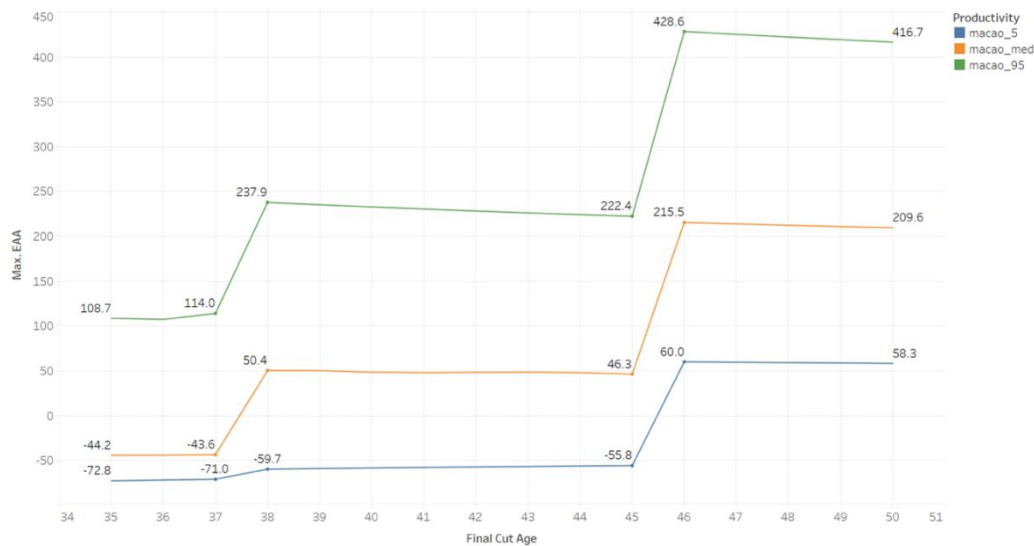


Figure 5.8: Sensitivity Analysis of the EAA with different Final cut ages

5.8.1.4 First harvesting process and regularity

The first harvesting operation typically occurs between the first 15 to 20 years of the stand, with subsequent intervals of 5 to 10 years (Centro Pinus 2015). Currently, the management approach of Mação includes three harvesting processes, the first at year 17, followed by two additional operations with intervals of 10 years. A sensitivity analysis was conducted with ranges of 15 to 20 years for the first operations and 5 to 10 years for intervals. A sorted heatmap, for each scenario, be seen in Figures 5.9, 5.10 and 5.11.

In each figure, the darker color marks the most profitable combination, while the lighter one marks the lowest NPV obtained. In all scenarios, the combinations that are marked with a darker color have intervals of 8 years. For *Mação 5* and *Mação 95* scenarios, this begins at year 16, while, for *Mação med* it is at year 15. However, due to the Wilson Factor criteria, the simulator only allows thinning in certain years. In *Mação 5*, thinning begins at year 32, so only two of the four operations scheduled are made. In *Mação med*, thinning starts at year 23, so, three out of four operations are made. In *Mação 95*, all scheduled thinning occurs, starting at year 16.

After assessing the actual performing thinning years, it is concluded that one additional operation is being done compared to Mação’s baseline. Since thinning directly contributes to wood and biomass receipts, one additional operation will impact positively the NPV.

By observing the NPV labeled in each figure, significant differences in the NPV yield are only seen on the lowest productivity scenario, while, on the other two, the differences are only of 7.58% and 1.3%. Given these findings, adjusting schedules may be most beneficial if in the presence of a lower productivity soil. Table V.3 summarizes the results found and can be seen in the Appendix V.4 Section.

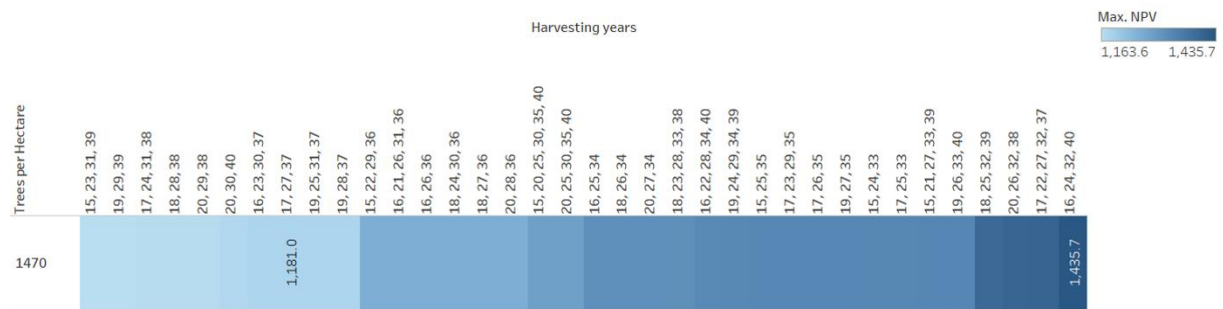


Figure 5.9: Sensitivity Analysis of the NPV with different Schedules, Mação 5

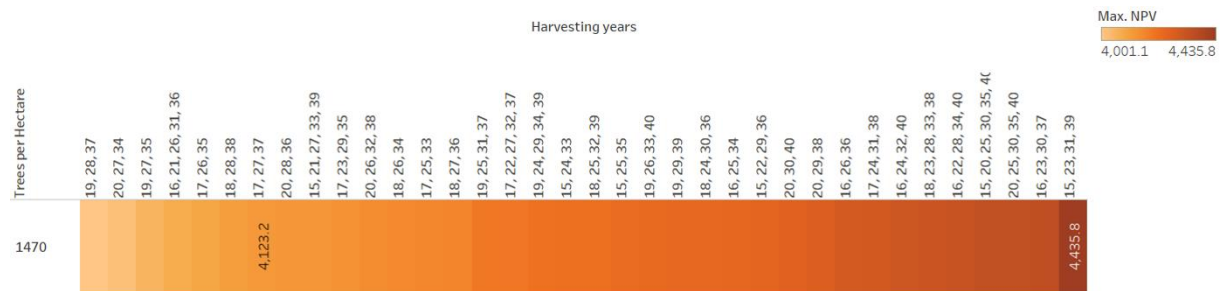


Figure 5.10: Sensitivity Analysis of the NPV with different Schedules, Mação med

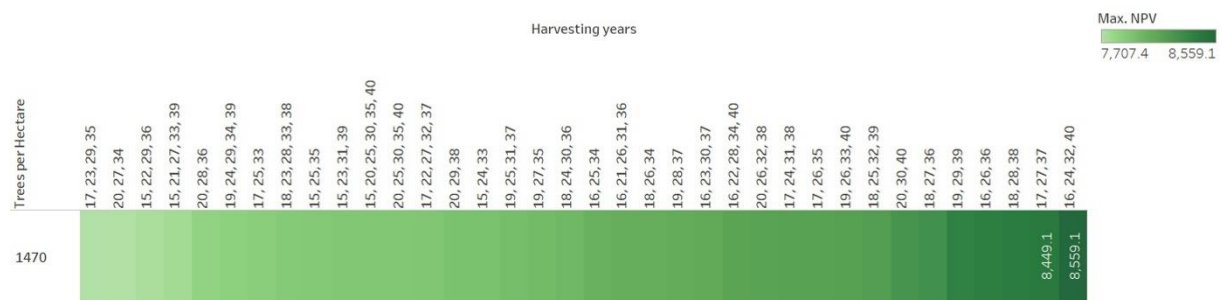


Figure 5.11: Sensitivity Analysis of the NPV with different Schedules, Mação 95

5.8.2 Multivariate Analysis

In the multivariate analysis, the main objective was to search for the optimal combination of parameters evaluated the univariate analysis. However, since the beat-up percentage is a complex parameter, and Mação provided information indicating that it is consistently around 15%, the results in this chapter are based on this fixed value.

The results obtained are shown in Table 5.3 and demonstrate that independently of the productivity scenario, the best planning horizon is 46 years. *Mação 5* continues to be the scenario that most benefits from parameter adjustments, with a 28% NPV increase, achieved by increasing the number of trees by 110 and the scheduling thinning to start at year 16 with 8-year intervals. Also, by revising some of the results obtained in [Section 5.8.1](#), we can see that by combining the optimal schedule with a tree density of 1,580, 10 less than the value obtained in the univariate analysis, the NPV increased.

For *Mação med*, the optimal tree density and schedule obtained in the univariate analysis remained the same, resulting in an increase of €721.8, 17.5%, when combined.

In *Mação 95*'s scenario, while the optimal tree density remained the same, 1,660, the thinning schedule changed to starting at year 15 with intervals of 8 years. If Mação decides to increase the number of trees planted for 1,660, applying the schedule obtained in this analysis, can enhance the NPV. Charts regarding this analysis can be found in the [Appendix V.4 Section](#).

Scenario	Type	Trees per Hectare	Beat-up Percent (%)	Schedule	Actual Performing Thinning years	Final Cut Age	NPV (€)	Difference (%)
Mação 5	Practiced	1470	15	(17, 27, 37)	(37)	46	1181.0	-
Mação 5	Max NPV	1580	15	(16, 24, 32, 40)	(32, 40)	46	1511.6	27.99
Mação med	Practiced	1470	15	(17, 27, 37)	(27, 37)	46	4123.2	-
Mação med	Max NPV	1670	15	(15, 23, 31, 39)	(23, 31, 39)	46	4845.0	17.5
Mação 95	Practiced	1470	15	(17, 27, 37)	(17, 27, 37)	46	8449.1	-
Mação 95	Max NPV	1660	15	(15, 23, 31, 39)	(15, 23, 31, 39)	46	9216.4	9.08

Table 5.3: Summary of Multivariate Sensitivity Analysis

5.9 Conclusion - Recommendations

After conducting both univariate and multivariate sensitivity analysis, recommendations on the best values to use in each parameter will be given so that Mação's overall returns are optimized.

5.9.1 Management schedule

In *Mação med*, the optimal schedule, regardless of other parameters' variation, remained the same, starting at year 15 with intervals of 8 between harvesting, making it the recommended schedule for medium site indexes. The same was observed for *Mação 5*, either with a lower or a higher number of trees per hectare, – 1,470 or 1,590, respectively – starting at year 16, with intervals of 8, might be beneficial, since the wood collected and available for selling is higher than with the base schedule.

In *Mação 95*, the management schedule differs between the multivariate and univariate sensitivity analysis. With 1,470 trees, the best schedule starts at year 16 with intervals of 8, while, with 1,660 trees, starting at year 15 with intervals of 8 marks the optimal point. Although, the NPV yield was higher when both a higher tree density and optimal schedule were combined, given Mação's characteristics, following the findings of the univariate might be more prudent.

5.9.2 Tree Density

In every productivity scenario, the analysis showed that planting more than 1,500 trees increases the NPV. However, Mação is a territory very affected by wildfires, meaning that planting the base 1,470 trees might be more prudent. By planting a lower tree density of trees, the territory is able to reduce the impact of a high intensity fire, and, at the same time, increase spacing between trees, lowering the competition between and enhancing their overall healthy growth.

5.9.3 Planning Horizon

As previously referred, Mação is territory highly vulnerable to fires, so, given its conditions, the life cycle of trees should be reduced to protect the municipality. Although it is usual to cut the stand at age 50, Mação usually harvests earlier, at the age of 46. As it was possible to see in the sensitivity analysis, the age of 46 is the most profitable for Mação, leading to the conclusion that that age might be the most appropriate to apply.

5.9.4 Beat-up Percentage

Lower beat-up percentages result in higher yields of the NPV. This fact shows the importance of making efforts to lower this percentage. Applying adequate soil preparation, planting techniques and preventive measures to reduce the impact of climate changes can directly impact the performance of the management approach followed.

5.9.5 Proposed Management Strategy

Considering Mação's characteristics and the results of sensitivity analysis, the following management approach is recommended to maximize returns while protecting from wildfires:

- Harvesting operations should have increments of 8, regardless of the productivity of the land. In the case of low and high-site indexes, the first harvest should be at year 16 and, in the case of a medium, it should start at year 15.
- Implement measures that lower the beat-up rate as much as possible, while maintaining both the 1,470 trees per hectare and the 46 years as the time horizon planning.

5.10 Limitations

The API design presented several limitations, mostly regarding the unavailability of site index data. Given this fact, the simulation could not accurately tell what to expect regarding the NPV. However, by using estimated site indexes, it was possible to address this challenge. Conversely, the same did not happen with prices, since the simulations relied on static prices provided by

Mação, which do not reflect market fluctuations or variations caused by land slope, as these operational cost differences were not considered.

StandsSIM, assumes a linear relationship between NPV, productivity, and the number of hectares, meaning that the simulations are conducted for one hectare only and the output values are multiplied by the number of hectares introduced by the user. In reality, variations such as tree spacing, competition or resource distribution can affect productivity differently in smaller or larger stands, differing from this linear assumption.

Lastly, the sensitivity analysis was very complete, accounting for the variation of all parameters, individually and collectively. Nevertheless, it was limited in exploring alternative management schedules besides harvesting years. Other operations, such as vegetation control timing, were not tested due to the lack of alternative management plans for maritime pine.

5.11 Future Work

Currently, the API only supports non-existent and even-aged stands. However, extending its functionalities to include more complex scenarios could significantly benefit users. Since StandsSIM already possesses these capabilities, incorporating them into the API would enhance its utility for LAND IT platform and, consequently, for its users. By offering a wider range of options and increasing the flexibility of allowed stand types for simulation, the API could extend its functionalities to a broader range of use cases and provide greater value.

Moreover, one limitation encountered was the fact that data necessary to perform an economic feasibility analysis of already existing maritime pine stands' in Mação, was not able to obtain in time duration of this thesis. However, it is of great importance that this data is collected and analyzed, to enable the integration of existing plantations into the API. This enhancement would allow LAND IT users to simulate not only new plantations but also existing ones.

References

European Commission. *Recovery plan for Europe*. European Commission.

https://commission.europa.eu/strategy-and-policy/recovery-plan-europe_en

População de Mação. 2001. "O Concelho." Accessed September 22, 2024.

<https://populacaodemacao.jimdofree.com/o-concelho/>.

Gabinete de Estratégia e Estudos (GEE). 2023. "Mação: Estatísticas Regionais." Accessed September 30, 2024. <https://www.gee.gov.pt/pt/lista-publicacoes/estatisticas-regionais/distritos-concelhos/santarem/macao/3190-macao/file>.

Médio Tejo. 2019. "Mação: Exemplo florestal elogiado em todo o mundo, mas em Portugal falta coragem política." Médio Tejo, November 15. Accessed September 30, 2024. <https://mediotejo.net/macao-exemplo-florestal-elogiado-em-todo-o-mundo-mas-em-portugal-falta-coragem-politica/>.

Fernandes, Patrícia, Fernando Miguel Granja-Martins, Celestina Pedras, and Helena Maria Fernandez. 2020. "Análise dos Incêndios no Município de Mação num Período de 30 Anos (1991–2019)." Universidade do Algarve, Faro.

ICNF (Instituto da Conservação da Natureza e das Florestas). 2019. *8.º Relatório Provisório de Incêndios Rurais de 2019*. Lisboa: ICNF.

ICNF (Instituto da Conservação da Natureza e das Florestas). 2017. *10.º Relatório Provisório de Incêndios Florestais -2017*. Lisboa: ICNF.

Câmara Municipal de Mação. 2021. *Propostas para o Concelho de Mação: Áreas Integradas de Gestão da Paisagem (AIGP)*. Mação: Câmara Municipal de Mação. Accessed September 24, 2024. <http://www.cm-macao.pt/index.php/pt/83-info-municipal/noticias/1146-propostas-concelho-macao-aigp>.

Direção-Geral do Território. 2023. *Ordenamento Integrado e Gestão da Paisagem (OIGP)*.

Acessed 17 October, 2024. <https://www.dgterritorio.gov.pt/paisagem/ptp/oigp>

Direção-Geral do Território. 2023. *Quadro de referência para o Ordenamento Integrado e*

Gestão da Paisagem - Versão 4 (2023-11-28). Accessed 17 October, 2024.

https://www.dgterritorio.gov.pt/sites/default/files/ficheiros-paisagem/Quadro_referencia_OIGP_versao4_20231128.pdf

Racius. 2024. "AZR Gestão Territorial, S.A." Accessed 24 September, 2024.

<https://www.racius.com/azr-gestao-territorial-s-a/>.

FCT (Faculdade de Ciências e Tecnologia). 2024. "Faculdade de Ciências e Tecnologia da

Universidade Nova de Lisboa." Accessed 24 September, 2024. <https://www.fct.unl.pt/>.

Instituto Superior de Agronomia. 2024. "Margarida Tomé – Investigadora." Accessed 24

September, 2024. <https://www.isa.ulisboa.pt/id/magatome>.

Instituto Superior de Agronomia. 2024. "Instituto Superior de Agronomia – Universidade de

Lisboa." Accessed 24 September, 2024. <https://www.isa.ulisboa.pt/>.

Mediatejo.net. 2023. "António Louro Renuncia ao Mandato na Câmara de Mação para se

Dedicar à Reforma da Floresta." Accessed 24 September, 2024.

<https://mediatejo.net/antonio-louro-renuncia-ao-mandato-na-camara-de-macao-para-se-dedicar-a-reforma-da-floresta/>.

Aflomacção – Associação Florestal do Concelho de Mação." Accessed 24 September, 2024.

<https://www.aflomacao.pt/>.

- ICNF (Instituto da Conservação da Natureza e das Florestas). 2019. *IFN6 – Principais Resultados – Relatório Sumário*. Lisboa: Instituto da Conservação da Natureza e das Florestas.
- Autoridade Florestal Nacional. 2012. *Regiões de Proveniência: Portugal*. Lisboa: Autoridade Florestal Nacional.
- Florestas.pt. 2023. "Pinheiro-bravo: A Conífera Mais Abundante em Portugal." Accessed September 24, 2024. <https://florestas.pt/conhecer/pinheiro-bravo-a-conifera-mais-abundante-em-portugal/>
- Figueiral, Isabel. 1995. "Charcoal Analysis and the History of *Pinus pinaster* (Cluster Pine) in Portugal." *Review of Palaeobotany and Palynology* 89(1-2): 441–454.
- Matias, Márcia Batalha. 2023. *Sistema de Apoio à Decisão para as Áreas Integradas de Gestão da Paisagem*. Mestrado em Engenharia Informática, Universidade NOVA de Lisboa.
- Oliveira, A. 1999. *Boas Práticas Florestais para o Pinheiro Bravo – Manual*. Porto: Centro Pinus – Associação para a Valorização da Floresta de Pinho.
- Centro Pinus. 2016. *Silvicultura: O Futuro é Crescer – Boas Práticas na Floresta de Pinheiro-Bravo*. Porto: Centro Pinus – Associação para a Valorização da Floresta de Pinho.
- Gonçalves, João, Pedro Teixeira, and Susana Carneiro. 2020. *Valorizar o Pinheiro-Bravo: A Perspetiva de Mercado*. Lisboa: Centro PINUS.
- Mendes, Amélia, Teresa Fonseca and Jorge Branco. 2017. *Pinhais Bravos: Um Sistema Baseado em Ecogestão de Povoamentos*. Lisboa: Instituto Superior de Agronomia. Accessed September 26, 2024.
- <https://www.repository.utl.pt/bitstream/10400.5/14258/1/Pinhais%20bravos-sbPbEcoges.pdf>.

Centro PINUS. 2015. *Manual de Boas Práticas: Melhoria da Gestão do Pinhal Bravo*. Porto: Centro PINUS. Accessed September 26, 2024.

https://www.centropinus.org/files/upload/edicoes_tecnicas/manual02.pdf.

Centro PINUS. *Centro PINUS – Associação para a Valorização da Floresta de Pinho*. Accessed September 26, 2024. <https://www.centropinus.org/>.

Centro PINUS. 2018. *Silvicultura do Pinhal Bravo: Recomendações Técnicas*. Porto: Centro PINUS. Accessed September 26, 2024.

https://www.centropinus.org/files/upload/edicoes_tecnicas/silvicultura-centro-pinus-digital.pdf.

Oliveira, Ângelo Carvalho, João Santos Pereira, and Alexandre Vaz Correia. 2000. *A Silvicultura do Pinheiro Bravo*. Porto: Centro Pinus.

Tomé, Margarida, Susana Barreiro, Joana Amaral Paulo, e Sónia Pacheco Faias. 2007. *Seleção de Equações para Estimação de Variáveis da Árvore em Inventários Florestais a Realizar em Portugal*. Lisboa: Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais.

Rodríguez-García, Aida, Rosana López, Juan Antonio Martín, Felix Pinillos, and Luis Gil. 2014. "Resin Yield in *Pinus pinaster* Is Related to Tree Dendrometry, Stand Density, and Tapping-Induced Systemic Changes in Xylem Anatomy." *Forest Ecology and Management* 313: 47–54.

ScienceDirect. 2024. "Pinus Pinaster." Accessed September 24, 2024.

<https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/pinus-pinaster>.

- Fernandes, Paulo, Hermínio Botelho, e Francisco Rego. 2005. "A Piroecologia do Pinheiro Bravo." *Silva Lusitana* 13(2): 233–248.
- Gómez-García, Esteban, Teresa F. Fonseca, Felipe Crecente-Campo, Luís R. Almeida, Ulises Diéguez-Aranda, Shongming Huang, and Carlos P. Marques. 2015. "Height-Diameter Models for Maritime Pine in Portugal: A Comparison of Basic, Generalized, and Mixed-Effects Models." *iForest* 9: 72-78.
- Alegria, Cristina Maria Martins. 2004. "PBIRROL: Modelo de Crescimento e Produção para os Povoamentos de Pinheiro Bravo de Estrutura Irregular do Concelho de Oleiros." Castelo Branco: Instituto Politécnico de Castelo Branco, Escola Superior Agrária.
- Alegria, Cristina Maria Martins. 2007. "Modelos para a Predição de Volumes do Pinheiro Bravo na Região de Castelo Branco." *Agroglobal* 19: 17-18.
- Ogana, Friday Nwabueze, Sacramento Corral-Rivas, and José Javier Gorgoso-Varela. 2020. "Nonlinear Mixed-Effect Height-Diameter Model for *Pinus pinaster* Ait. and *Pinus radiata* D. Don." *Cerne* 26(1): 150–161.
- Msaouak, Khaoula. 2016. "Modeling Height-Diameter Relationship in *Pinus pinaster* Ait. in the Forest Intervention Zone of Lomba, NE-Portugal." Master's thesis, Escola Superior Agrária, Instituto Politécnico de Bragança.
- Barreiro, Susana, João Rua, and Margarida Tomé. 2016. "StandsSIM-MD: A Management Driven Forest Simulator." *Forest Systems* 25(2): eRC07. <https://doi.org/10.5424/fs/2016252-08916>.
- ICNF (Instituto da Conservação da Natureza e das Florestas). 2021. *Plano Nacional de Gestão Integrada de Fogos Rurais (PNGIFR) – Relatório de Progresso 2021*. Lisboa: ICNF. Accessed October 23, 2024. <https://www.icnf.pt/api/file/doc/73ec1b0d36d0261f>.

ICNF (Instituto da Conservação da Natureza e das Florestas). 2022. *Projeto de (Re)Arborização – Envendos (B50)*. Lisboa: ICNF.

Produtores Florestais. 2024. "As Melhores Opções na Plantação." Accessed November 2, 2024. <https://www.produtorestlorestais.pt/as-melhores-opcoes-na-plantacao/>.

Centro de Estudos Florestais (CEF). 2022. *FMM5 – Forest Management Model Version 5*. Lisboa: Instituto Superior de Agronomia. Accessed November 3, 2024. https://www.isa.ulisboa.pt/cef/wp-content/uploads/2022/08/FMM5_v2.pdf.

Appendix

Appendix II - Mação

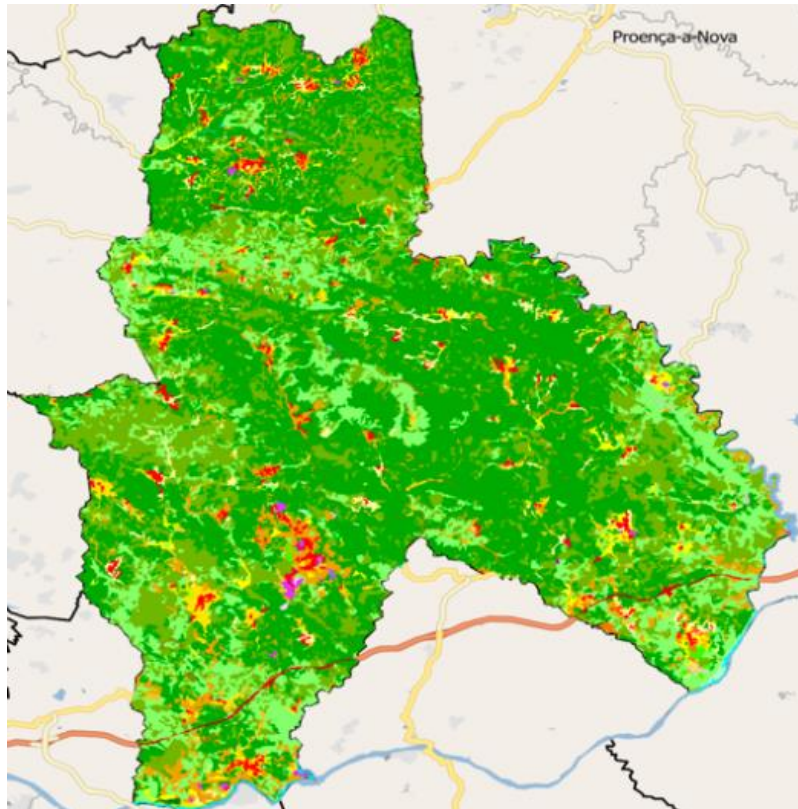


Figure II.1: COS Map | Source: Matias 2023

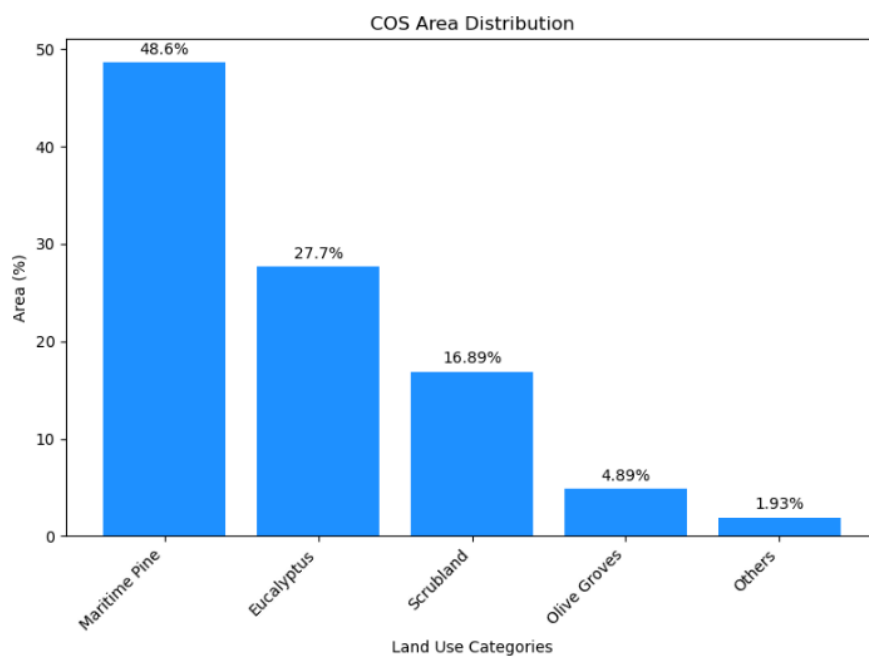


Figure II.2: COS Area distribution

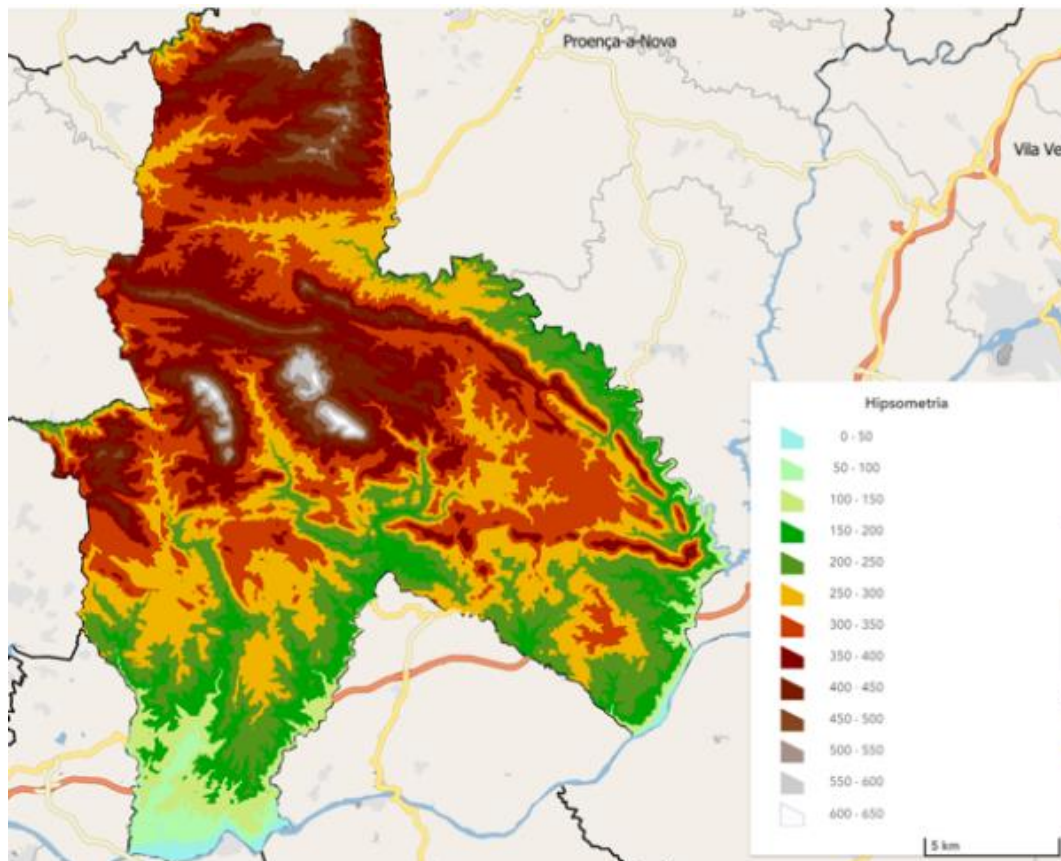


Figure II.3: Hypsometry in Mação

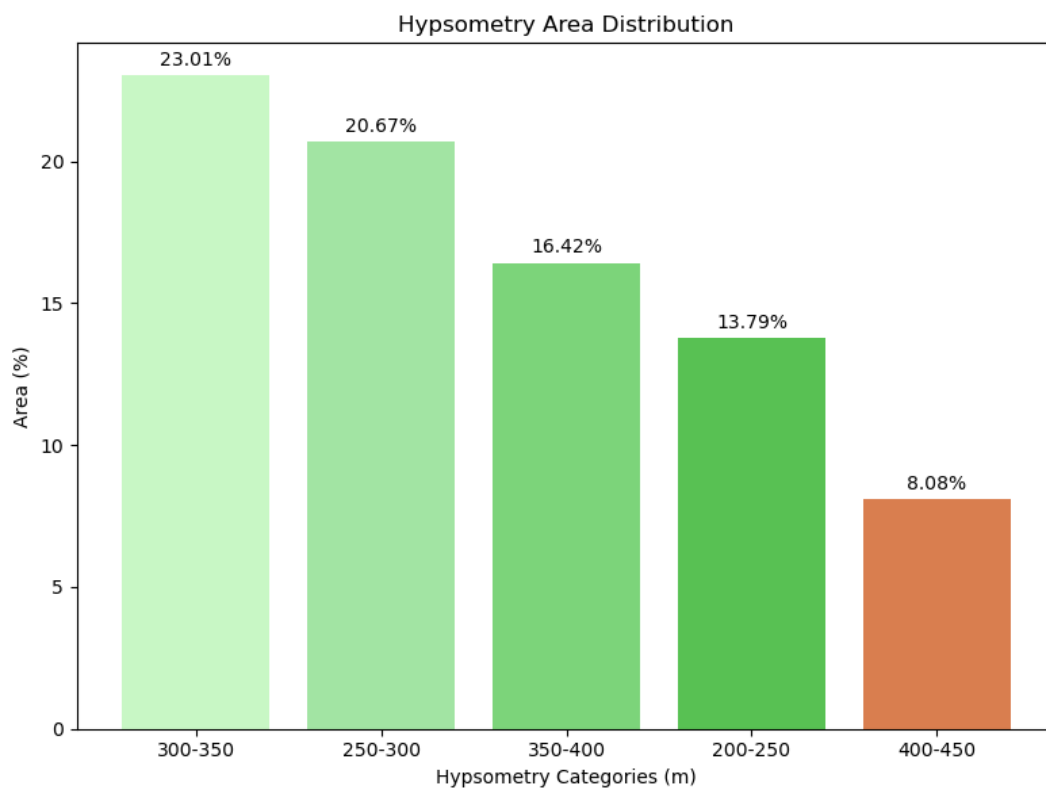


Figure II.4: Map Hypsometry in Mação | Source: Matias 2023

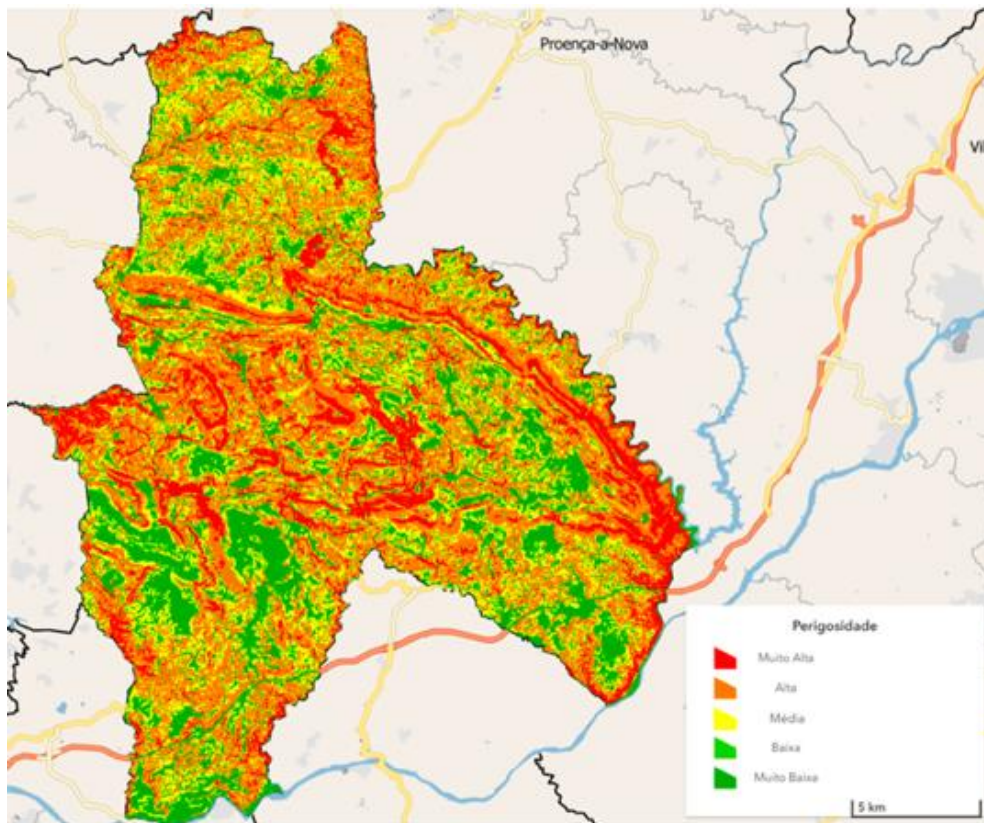


Figure II.5: COS Hypsometry in Mação

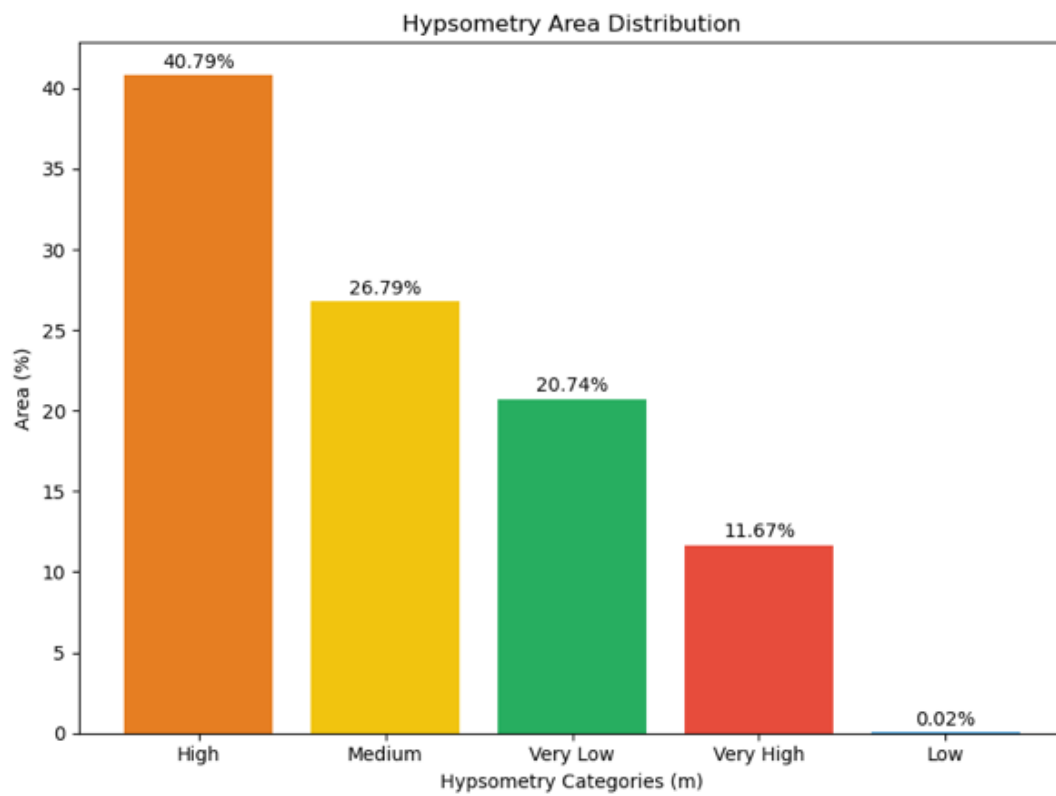


Figure II.6: COS Map Mação | Source: [Matias 2023](#)

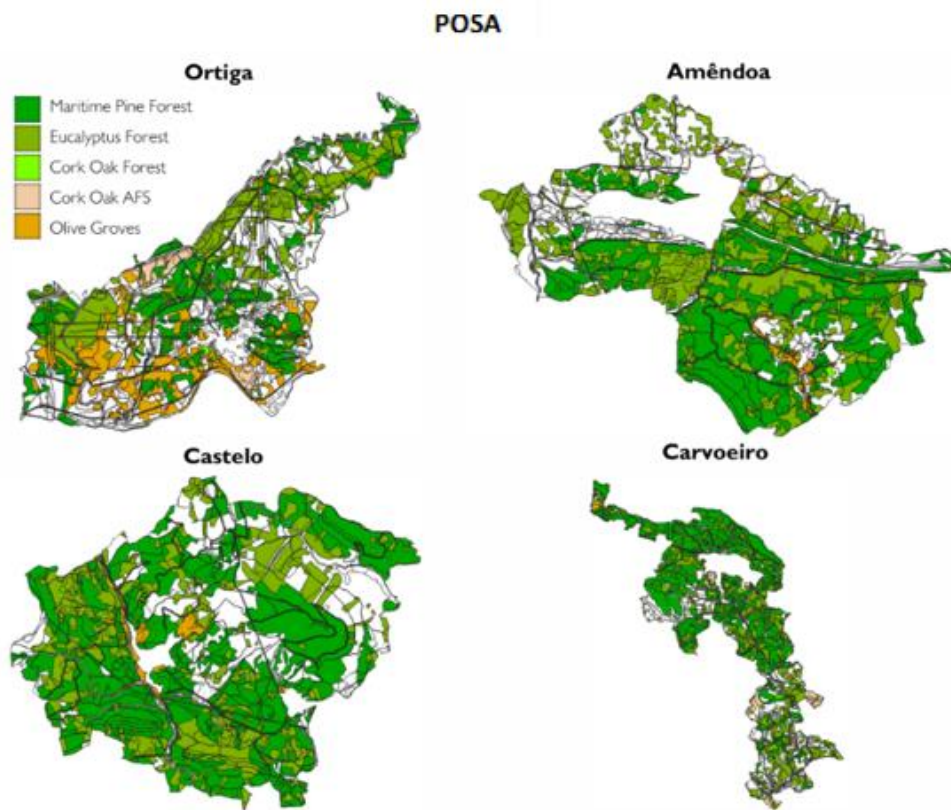


Figure II.7: Current Land Use Map in four specific AIGPs

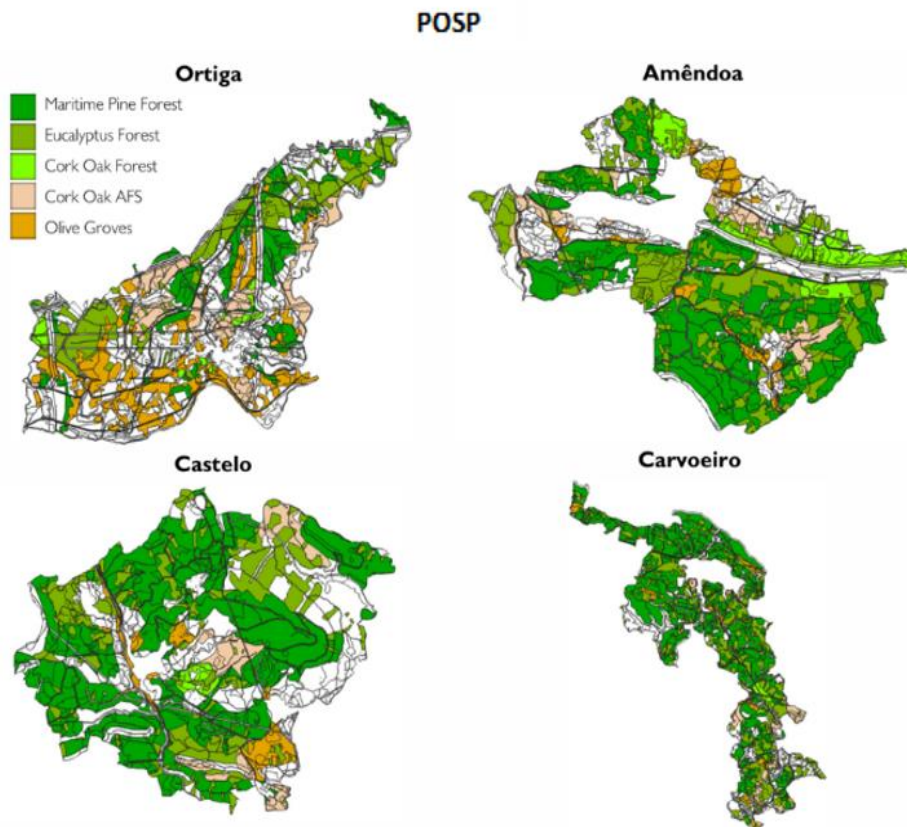


Figure II.8: Proposed Land Use Map in four specific AIGPs

Appendix IV – StandsSIM

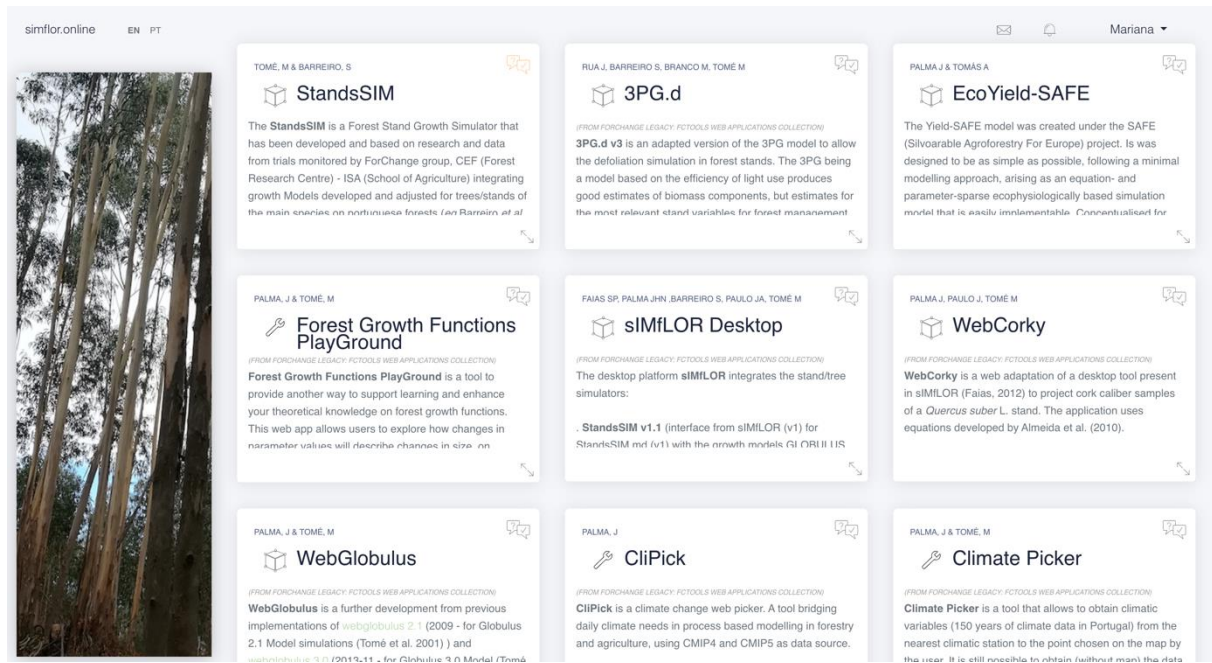


Figure IV.4 – StandsSIM output file: output_yieldtabl

Appendix V.1: Growing Cycle

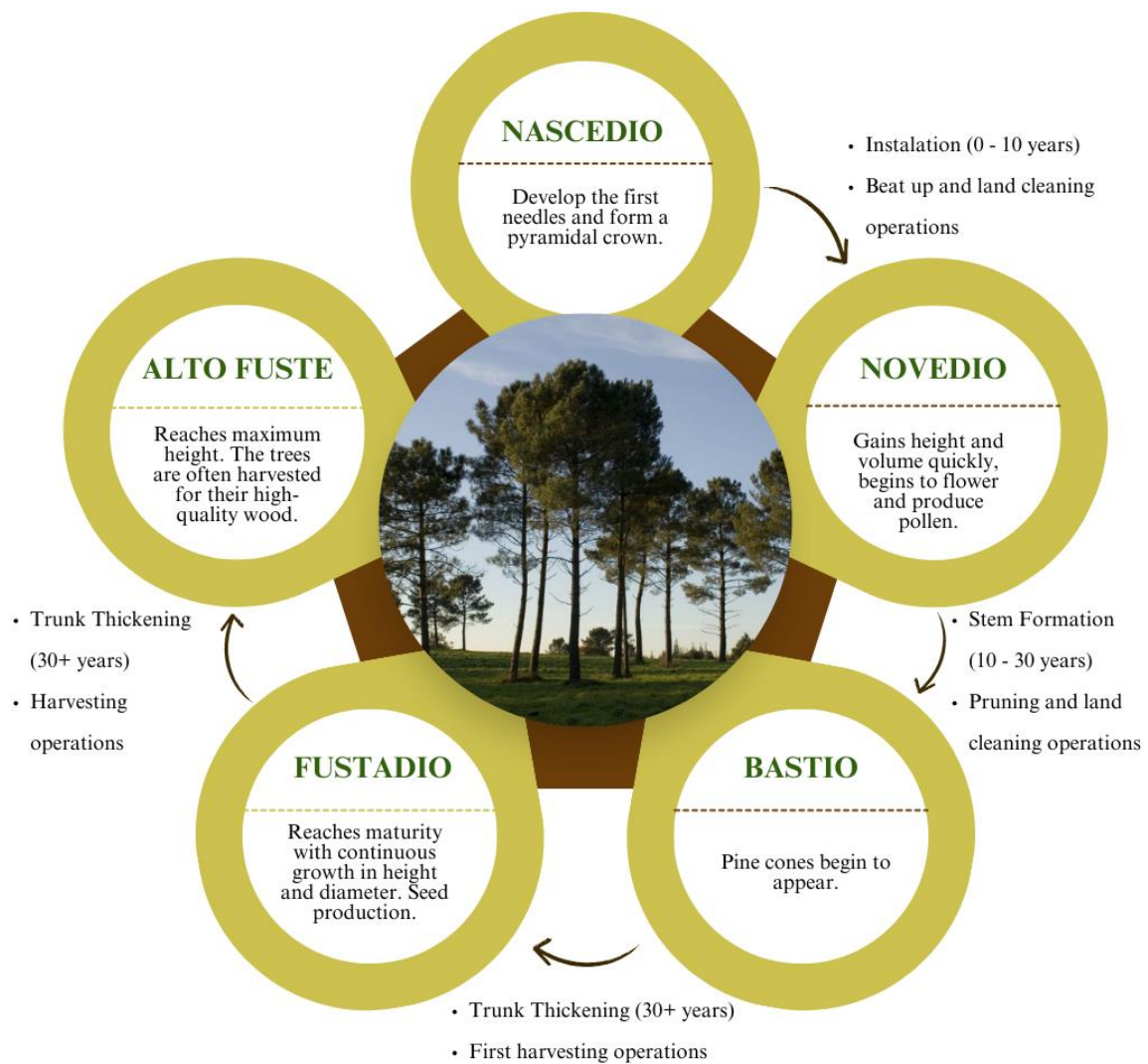


Figure V.1: Diameter and height variations in maritime pine (Matias, 2023)

Appendix V.2: Developed Models - Growth and Economic Model

The first goal was to develop a mathematical model to predict growth and economic return from maritime pine stands. This model aimed to simulate the lifecycle revenue generated from wood, resin and biomass, using user-provided data, such as the management that would be practiced

in terms of thinning and final cut processes, as well as some characteristics of the stand itself, more properly, its age.

To begin, equations for calculating wood volume and biomass weight were adopted from existing research. For wood volume, Equation 1 was used,

$$(1) \text{ } Pvudi = e^{-1,41300 * \left(\frac{d_i^{4,3488}}{d^{4,3188}} \right)}, \text{ with } d_i = d \left(-2,1823 * \left(\frac{h_i}{h} - 1 \right) + 0,8591 * \left(\frac{h_i^2}{h} - 1 \right) \right)^{0.5}$$

Equation 1: Equation selected for estimating the merchantable wood volume of Maritime Pine (excluding stump and bark) (Tomé et al. 2007)

In this equation, d_i represents the diameter of an individual tree, in centimeters, measured at 1.30 m height h is the total height of the tree, d represents the diameter of an individual tree, in centimeters, measured at 1.30 m height, h_i is the total height of the tree, d_i is the diameter measured at height h_i and $Pvudi$ is the proportion of volume without bark and stump, up to the topping diameter d_i .

For biomass, separate Equations 2, 3 and 4 were applied to estimate the weight of the tree's bark, branches and needles,

$$(2) \text{ } wb = 0,0114 * d^{1,8728} * h^{0,6694},$$

$$(3) \text{ } wbr = 0,00308 * d^{2,75761} * \left(\frac{h}{d} \right)^{-0,39381}$$

$$(4) \text{ } wl = 0,09980 * d^{1,39252} * \left(\frac{h}{d} \right)^{-0,71962}$$

Equations 2, 3, 4: Equations for estimating biomass weight (Tomé et al. 2007)

where (2), (3) and (4) represent the weight of the biomass, in kg, of the tree's bark, branches and needles respectively.

When it comes to resin's production, no equation was found, however, in average, trees with higher resin production were taller and thicker than trees with lower production (Rodríguez-García et al 2014), which means that both height and diameter are variables that have an influence in the amount of resin that can be extracted from a maritime pine.

While developing the model, several limitations were found, the primary one being the fact that there was no reliable age-dependent equation that accurately modeled the progression of height and diameter over the life cycle of *Pinus pinaster*. Accurate predictions for these attributes are essential because they directly influence calculations of wood volume, biomass weight, and resin production, which are the primary revenue sources for maritime pine stands.

Moreover, the initial modelling intention was to treat each tree individually, since that is how maritime pine stands are treated, however this approach required a more precise modelling that could capture the variations in individual growth patterns, which was not possible due to the lack of data.

Appendix V.3: Results Analysis

Dominant Height

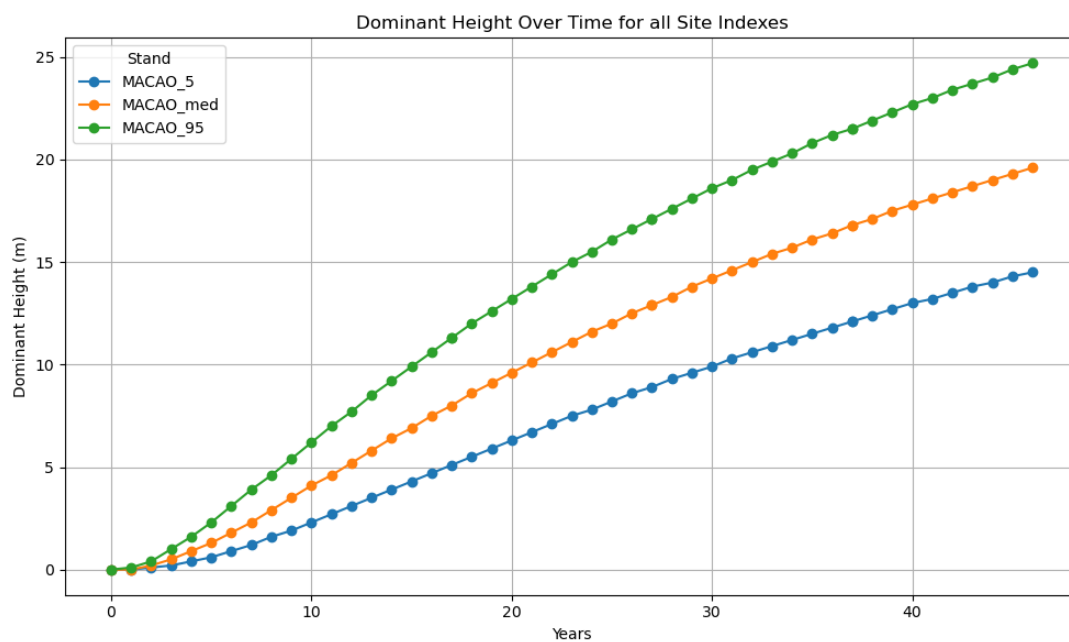


Figure V.2: Dominant Height over time for three site indexes

Number of trees

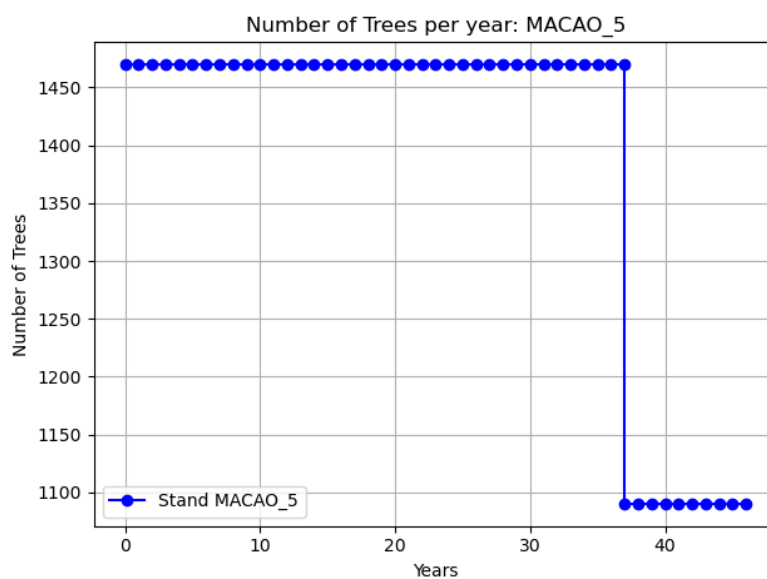


Figure V.3: Number of trees over time for Mação 5

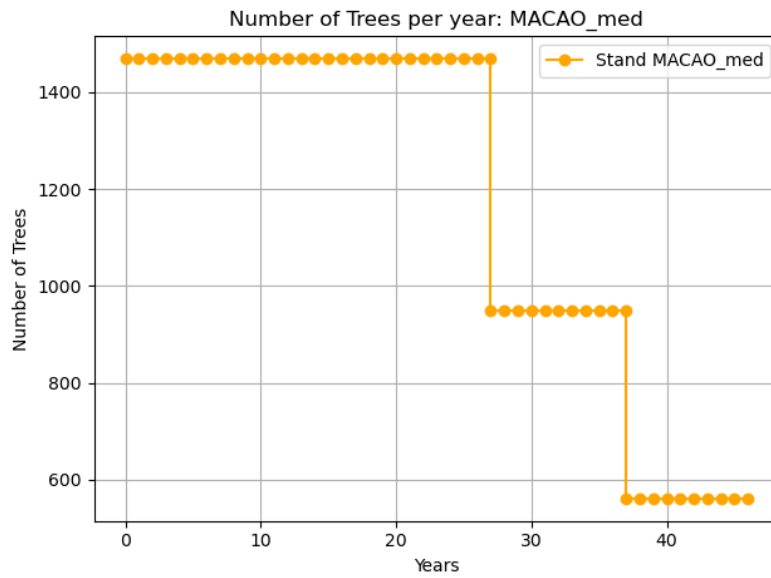


Figure V.4: Number of trees over time for Mação Med

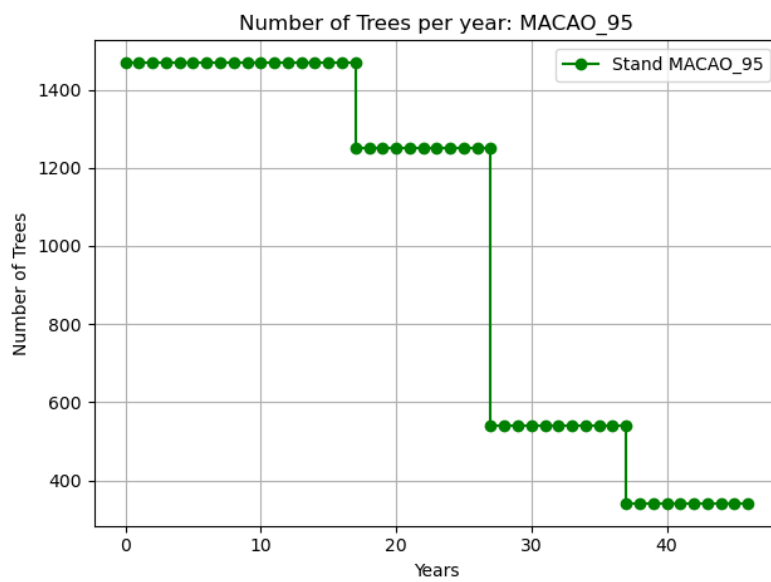


Figure V.5: Number of trees over time for Mação 95

Basal area and Wood Volume

Basal area consists in the total cross-sectional area of all tree trunks, at 1.3 meters above ground, per hectare and is a key measure for forest management and health assessment, since it indicates forest density, productivity and competition among trees.

As expected, in Figure V.6 is visible that *Mação 95* scenario has the highest wood volume, while *Mação 5* has the lowest. The growth in wood volume accelerates significantly after the initial phase and the lowest values, coordinated in all three scenarios, represent harvesting operations.

Moreover, higher productivity sites generally result in higher tree density and faster growth, consequently, leading to a higher basal area. In contrast, lower site indexes show the slowest growth in basal areas, with slower growth rates and fewer economic viable trees. These facts are clearly represented in Figure V.7, *Mação 95*, the higher productivity scenario, has high basal area, while *Mação 5* shows a clear slowest growth in basal area over the time.

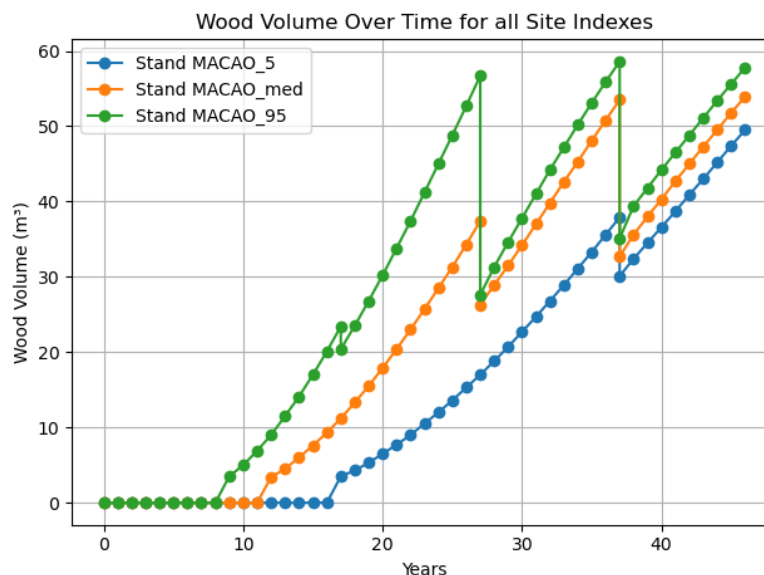


Figure V.6: Wood volume over time for all site indexes

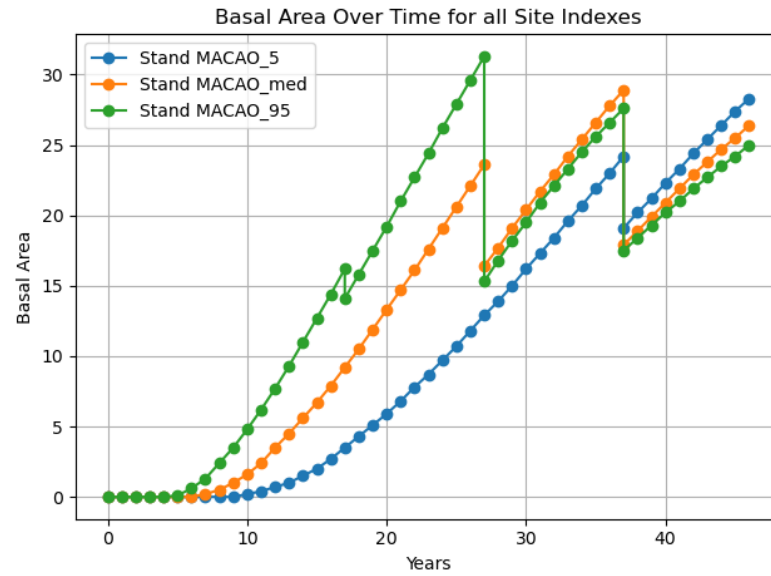


Figure V.7: Basal area over time for three site indexes

EAA, NPV and NPV Sum

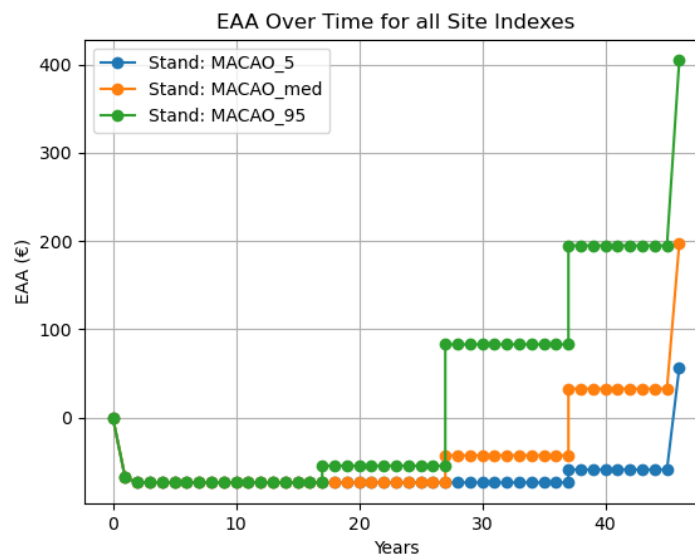


Figure V.8: EAA over time for three site indexes

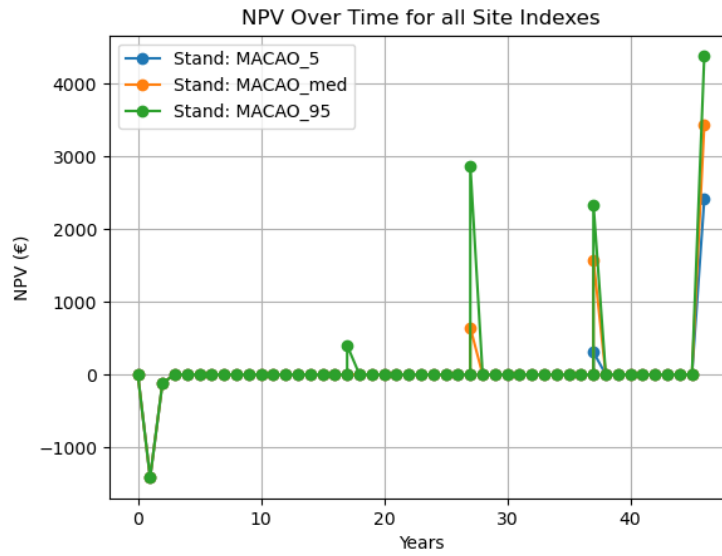


Figure V.9: NPV over time for three site indexes

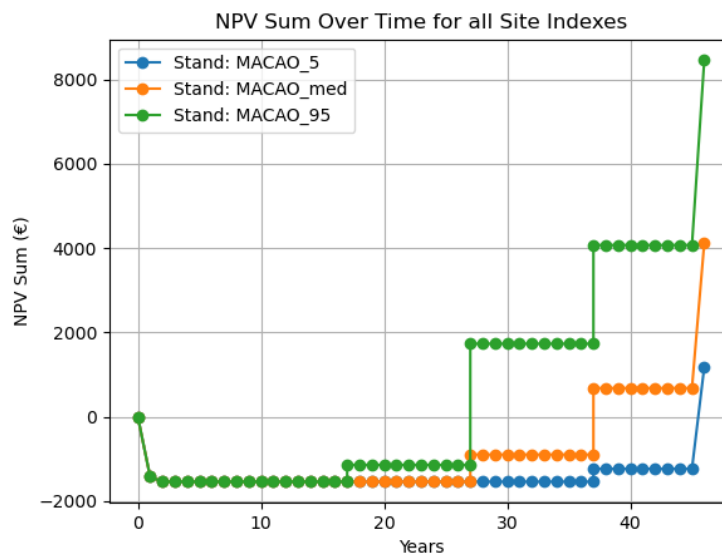


Figure V.10: Cumulative NPV over time for three site indexes

Appendix V.4: Sensitivity Analysis

Number of trees

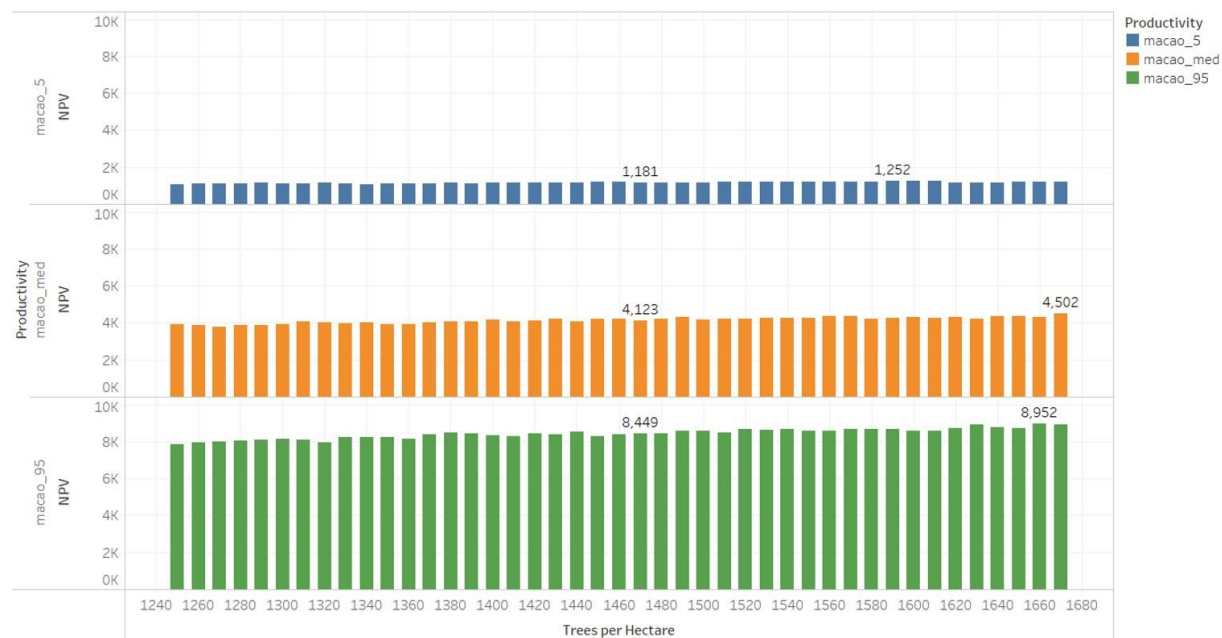


Figure V.11: Sensitivity Analysis of NPV with number of trees per hectare, for all three scenarios

Scenario	Type	Trees per hectare	NPV (€)	Difference (%)
Mação 5	Max NPV	1590	1252.2	6.03
Mação 5	Practiced	1470	1181.0	-
Mação med	Max NPV	1670	4501.6	9.18
Mação med	Practiced	1470	4123.2	-
Mação 95	Max NPV	1660	8951.8	5.95
Mação 95	Practiced	1470	8449.1	-

Table V.1: Summary of Sensitivity Analysis of NPV with Number of Trees per hectare

Beat-up Rate

Scenario	Site Index	Beat-up Percent (%)	NPV (€)	Difference (%)
Mação 5	15.44	5	1341.8	-
Mação 5	15.44	10	1261.4	-5.99
Mação 5	15.44	15	1181.0	-11.98
Mação 5	15.44	20	1100.6	-17.98
Mação 5	15.44	25	1020.2	-23.97
Mação med	20.69	5	4284.0	-
Mação med	20.69	10	4203.6	-1.88
Mação med	20.69	15	4123.2	-3.75
Mação med	20.69	20	4042.8	-5.63
Mação med	20.69	25	3962.4	-7.51
Mação 95	25.86	5	8609.9	-
Mação 95	25.86	10	8529.5	-0.93
Mação 95	25.86	15	8449.1	-1.87
Mação 95	25.86	20	8368.7	-2.8
Mação 95	25.86	25	8288.3	-3.74

Table V.2: Summary of Sensitivity Analysis of the NPV with different Beat-up percentages

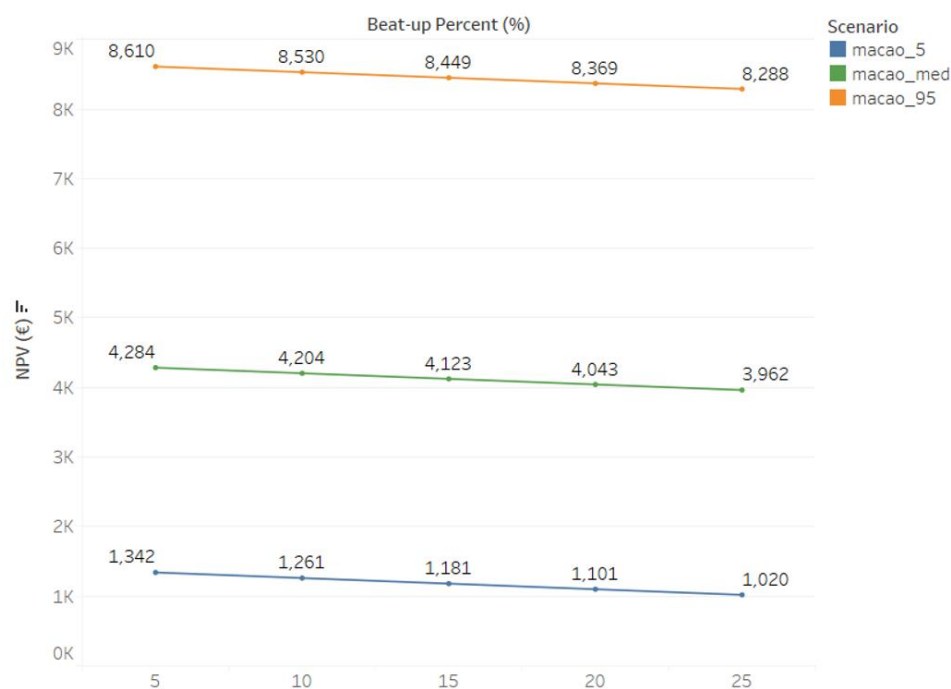


Figure V.12: Sensitivity Analysis of NPV with Beat-up percentages

Final Cut ages

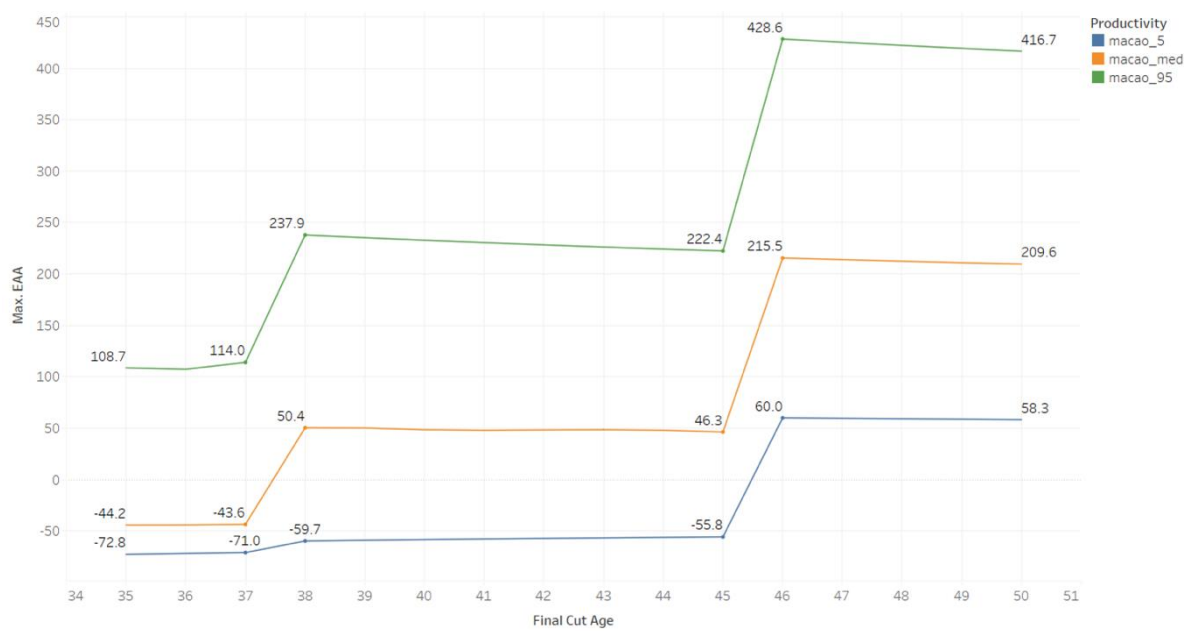


Figure V.13: Sensitivity Analysis of the NPV with different Final cut ages

Management Schedules

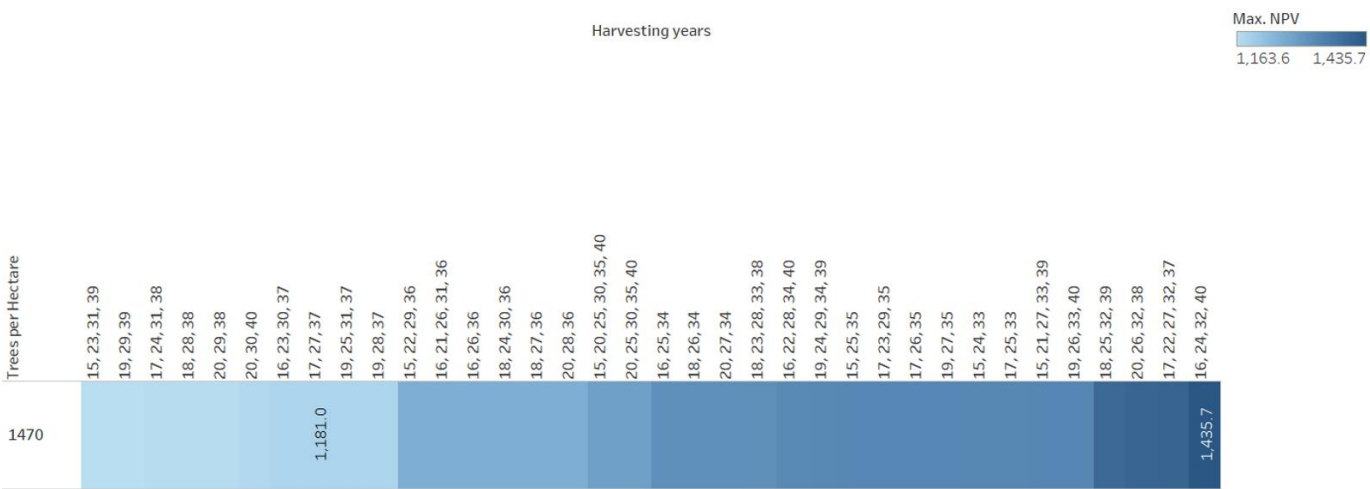


Figure V.14: Sensitivity Analysis of NPV with management schedules, Mação 5

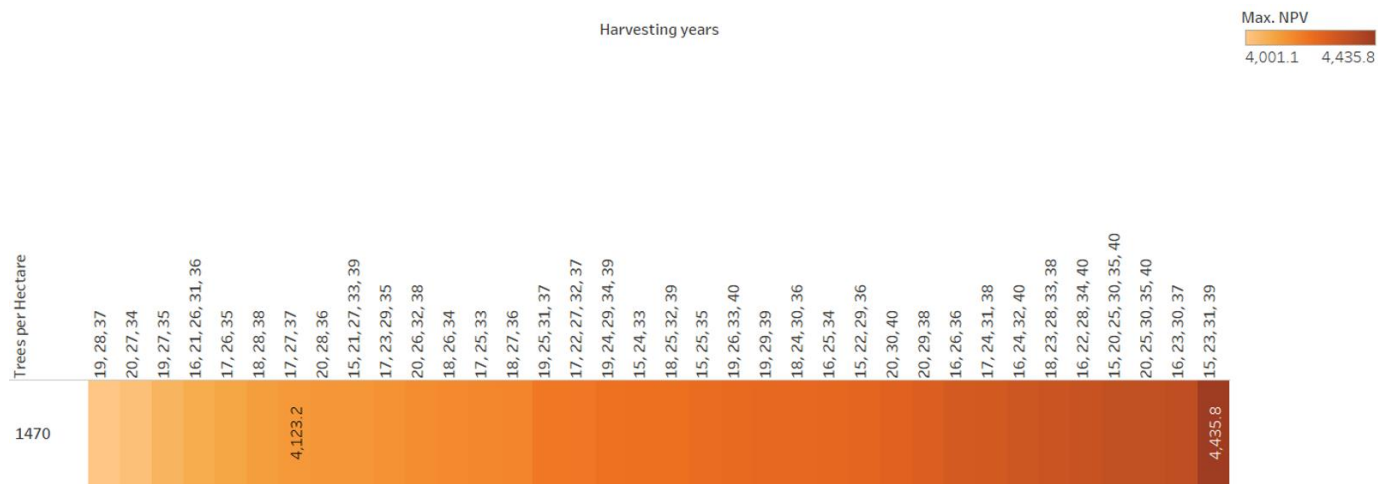


Figure V.15: Sensitivity Analysis of NPV with management schedules, Mação med

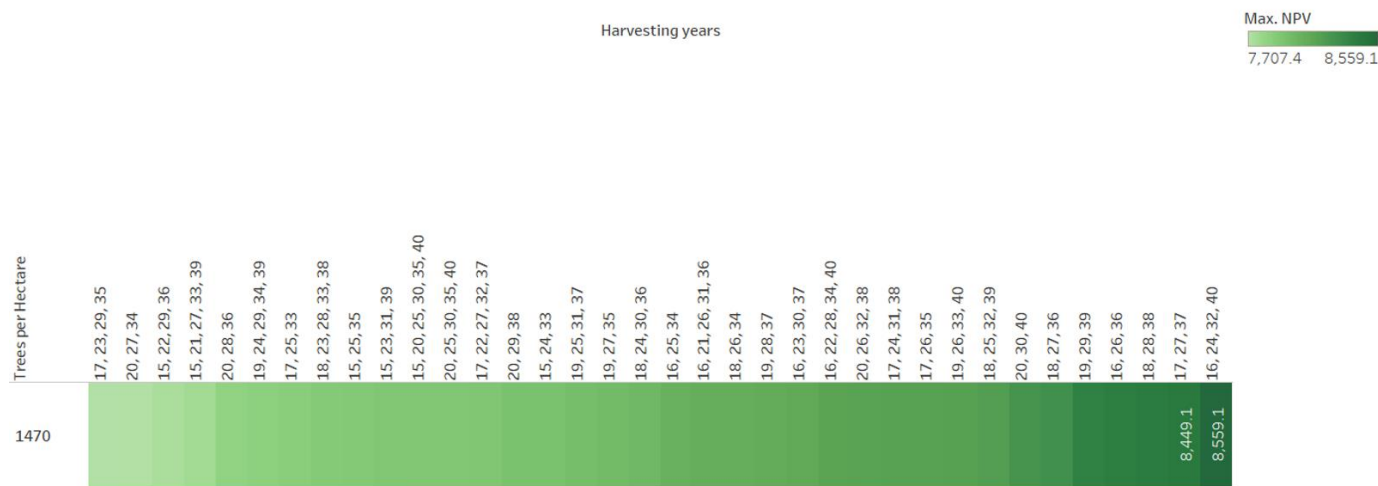


Figure V.16: Sensitivity Analysis of NPV with management schedules, Mação 95

Scenario	Type	Schedule	Actual Performing Thinning years	NPV (€)	Difference (%)
Mação 5	Max NPV	(16, 24, 32, 40)	(32, 40)	1435.7	21.57
Mação 5	Practiced	(17, 27, 37)	(37)	1181.0	-
Mação med	Max NPV	(15, 23, 31, 39)	(23, 31, 39)	4435.8	7.58
Mação med	Practiced	(17, 27, 37)	(27, 37)	4123.2	-
Mação 95	Max NPV	(16, 24, 32, 40)	(16, 24, 32, 40)	8559.1	1.3
Mação 95	Practiced	(17, 27, 37)	(17, 27, 37)	8449.1	-

Table V.3: Summary of the Sensitivity Analysis of the NPV with different management schedules

Multivariate sensitivity analysis

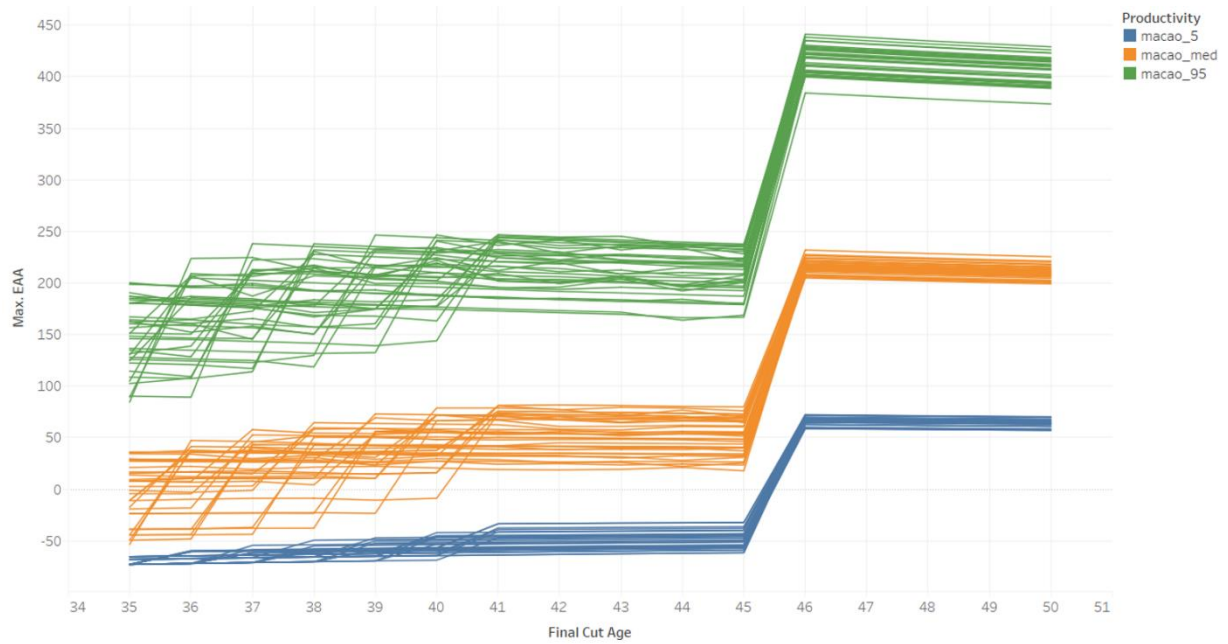


Figure V.17: Multivariate Analysis: Final Cut Age vs. Max EAA.

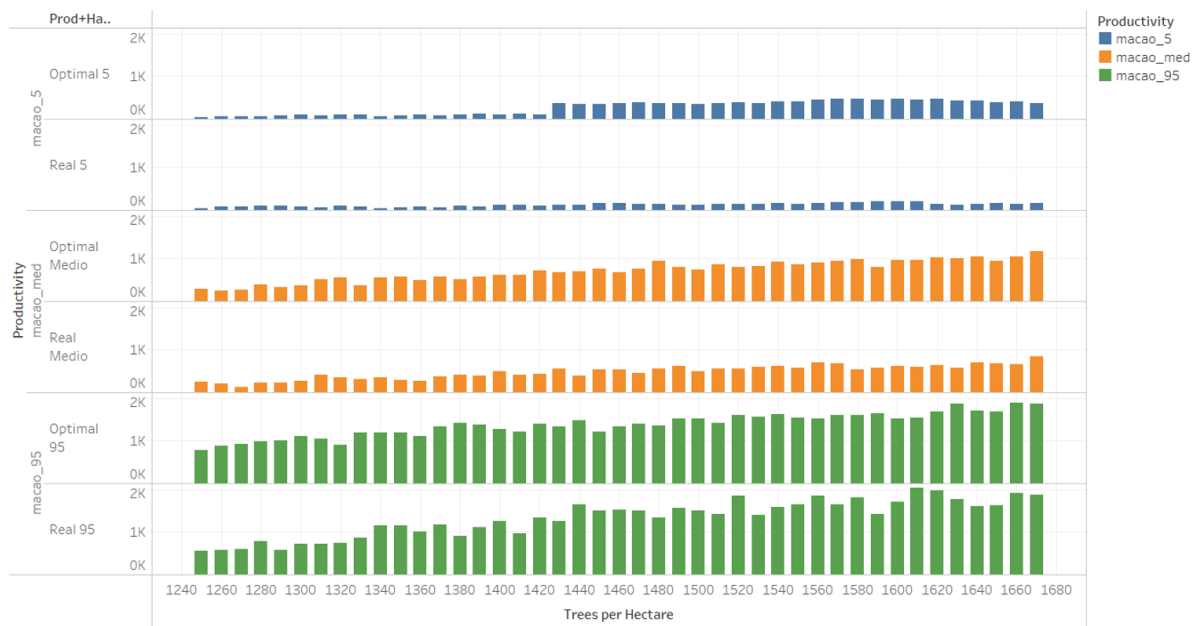


Figure V.18: Multivariate Analysis: Visualization of every combination of trees between the optimal and practiced schedules for all three productivity scenarios.

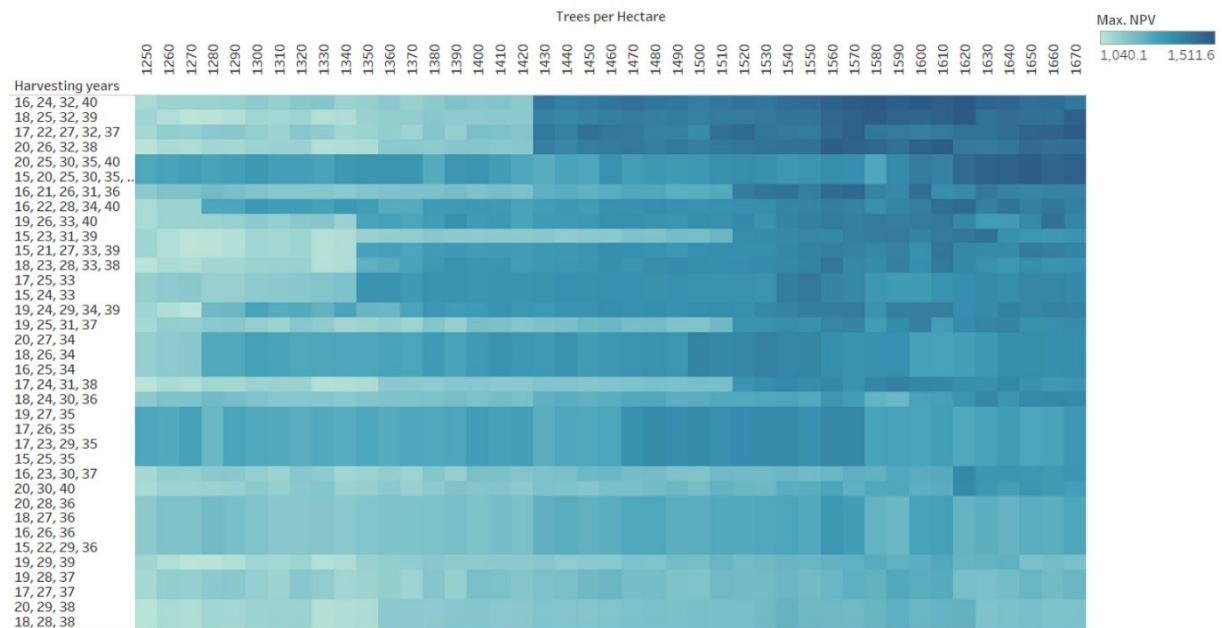


Figure V.19: Multivariate Analysis: Max NPV - Harvesting years vs. Trees per Hectare, Mação 5

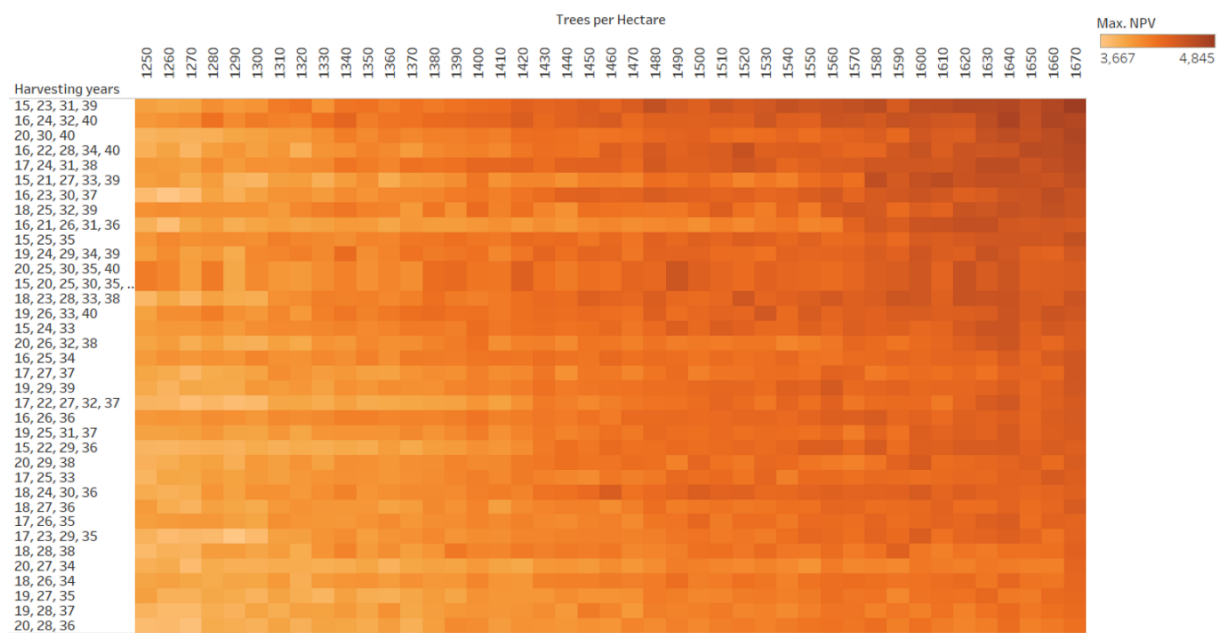


Figure V.20: Multivariate Analysis: Max NPV - Harvesting years vs. Trees per Hectare, Mação med

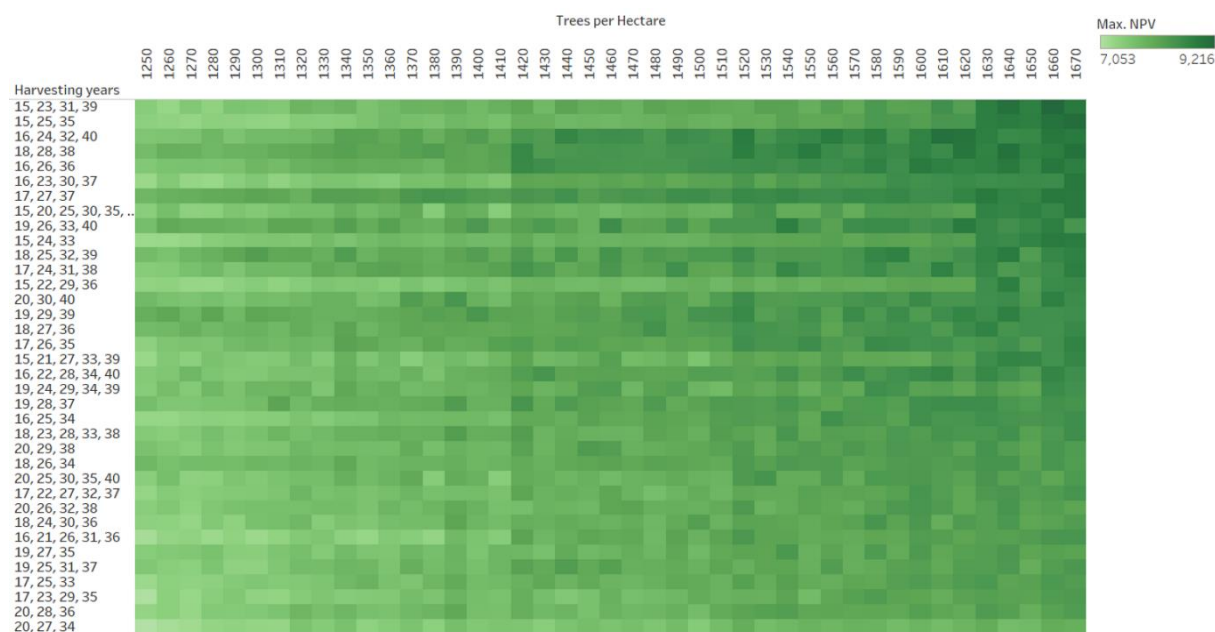


Figure V.21: Multivariate Analysis: Max NPV - Harvesting years vs. Trees per Hectare, Mação 95

Scenario	Type	Trees per Hectare	Beat-up Percent (%)	Schedule	Actual Performing Thinning years	Final Cut Age	NPV (€)	Difference (%)
Mação 5	Practiced	1470	15	(17, 27, 37)	(37)	46	1181.0	-
Mação 5	Max NPV	1580	15	(16, 24, 32, 40)	(32, 40)	46	1511.6	27.99
Mação med	Practiced	1470	15	(17, 27, 37)	(27, 37)	46	4123.2	-
Mação med	Max NPV	1670	15	(15, 23, 31, 39)	(23, 31, 39)	46	4845.0	17.5
Mação 95	Practiced	1470	15	(17, 27, 37)	(17, 27, 37)	46	8449.1	-
Mação 95	Max NPV	1660	15	(15, 23, 31, 39)	(15, 23, 31, 39)	46	9216.4	9.08

Table V.4: Summary of Multivariate Sensitivity Analysis