Universidade de Évora - Instituto de Investigação e Formação Avançada
Universidade do Algarve - Faculdade de Ciências e Tecnologia

Programa de Doutoramento em Ciências Agrárias e Ambientais

Tese de Doutoramento

Impacte das alterações climáticas na variabilidade ambiental e na definição de estratégias para a floresta portuguesa: o controlo de espécies invasoras pela valorização energética

Leonel Jorge Ribeiro Nunes

Orientador(es) | Carlos José Gomes
Nuno de Almeida Ribeiro
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Dedico este trabalho a todos aqueles
que mesmo não estando, estão.

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Impacte das Alterações Climáticas na Variabilidade Ambiental e na Definição de Estratégias para a Floresta Portuguesa: o Controlo de Espécies Invasoras pela Valorização Energética

Resumo

O presente Trabalho incide sobre o impacto das alterações climáticas na floresta portuguesa, analisando a sua influência na variabilidade dos parâmetros ambientais e propondo novas estratégias de gestão florestal que contribuam para o aumento da resiliência das florestas. A problemática das espécies invasoras e o seu controlo através da valorização energética é um dos eixos centrais deste trabalho.

As alterações climáticas têm impactado diretamente as florestas portuguesas. Aumentos na temperatura média do ar, redução da precipitação e concentração dos períodos de precipitação levaram ao aumento do risco de fogos rurais e à propagação de espécies invasoras. Estes impactos, aliados ao abandono das zonas rurais, exigem a definição de novas estratégias de gestão florestal.

Neste trabalho confirma-se que as alterações nos parâmetros ambientais têm contribuído para a ocorrência de períodos de seca recorrentes, com efeitos diretos na floresta. Esta situação tem também contribuído para o aumento do risco de fogos rurais, enfraquecendo a floresta e permitindo a dispersão de espécies invasoras. Este ciclo prejudica a resiliência da floresta e incentiva a aplicação de ações que mitiguem estes impactos negativos.

A valorização energética da biomassa resultante das operações de controlo e erradicação de espécies invasoras surge como uma possibilidade a considerar. Esta abordagem permite recuperar grandes quantidades de biomassa residual, mantendo pressão constante sobre os povoamentos de espécies invasoras e reduzindo a sua capacidade de recuperação.

Propõe-se a adoção de modelos de gestão florestal adaptativos e multifuncionais. Estes modelos são dinâmicos, baseando-se a tomada de decisão nas medidas a implementar no pressuposto de que a gestão florestal deve ser enquadrada de forma abrangente, incluindo a análise de todas as variáveis. O recurso não só é valorizado, como potenciado.

A pesquisa enfrentou desafios significativos, nomeadamente a pandemia COVID-19, que limitou a capacidade de recolha de amostras e interação direta entre os participantes. No entanto, apesar das dificuldades, foi possível concluir o trabalho de caracterização prática de amostras de biomassa em laboratório.

Os temas discutidos nesta tese justificam maior profundidade e dedicação, e este trabalho serve para abrir um conjunto de possibilidades para futuras pesquisas. A intenção é dar continuidade ao estudo das alterações climáticas e dos modelos de gestão florestal, principalmente na identificação de processos para a recuperação da biomassa residual até ao seu pleno potencial, mas dando foco preferencial à recuperação energética através de processos de conversão termoquímica.

A conclusão deste trabalho não significa o fim dos temas discutidos, mas sim o início de novas possibilidades de investigação. Entre os temas abordados, as alterações climáticas certamente serão o impulso para continuar a pesquisa, analisando o impacto das mesmas no desenvolvimento de algumas espécies através do estabelecimento de modelos de crescimento para espécies lenhosas invasoras. Além disso, pretende-se estabelecer um modelo de correlação entre o crescimento de algumas espécies lenhosas e parâmetros como a precipitação e temperatura, que podem servir como um modelo para caracterizar o clima em locais onde dados não estão disponíveis.

Propõe-se a continuação da análise dos modelos de gestão florestal, principalmente na identificação de processos para a recuperação da biomassa residual até ao seu pleno potencial, mas dando preferencialmente foco à recuperação energética através de processos de conversão termoquímica, como a torrefação, a pirólise ou a gaseificação, combinados com a análise de cadeias de fornecimento baseadas na floresta, numa perspetiva de sustentabilidade dos recursos e da introdução de práticas de bioeconomia circular.

Palavras-chave: alterações climáticas; gestão florestal; espécies invasoras; valorização energética; bioeconomia circular.

Impact of Climate Change on Environmental Variability and Defining Strategies for the Portuguese Forest: Control of Invasive Species through Energy Valorization

Abstract

This doctoral thesis focuses on the impact of climate change on Portuguese forests, examining its influence on the variability of environmental parameters and proposing new forest management strategies that contribute to increasing forest resilience. The issue of invasive species and their control through energy recovery is one of the central themes of this work.

Climate change has directly impacted Portuguese forests. Increases in average air temperature, reduction of precipitation, and concentration of rainfall periods have led to an increased risk of rural fires and the spread of invasive species. These impacts, coupled with rural depopulation, necessitate the definition of new forest management strategies.

This thesis confirms that changes in environmental parameters have contributed to the occurrence of recurring drought periods, with direct effects on the forest. This situation has also contributed to the increased risk of rural fires, weakening the forest and allowing the dispersal of invasive species. This cycle damages forest resilience and encourages the application of actions to reduce/mitigate these negative impacts.

The energy recovery of biomass resulting from the control and eradication operations of invasive species emerges as a consideration. This approach allows the recovery of large quantities of residual biomass, maintaining constant pressure on stands of invasive species and reducing their recovery capacity.

The thesis proposes the adoption of adaptive and multifunctional forest management models. These models are dynamic, with decision-making based on the measures to be implemented on the assumption that forest management should be encompassed comprehensively, including the analysis of all variables. The resource is not only valued but also enhanced.

The research faced significant challenges, including the COVID-19 pandemic, which limited the capacity for sample collection and direct interaction between participants. However, despite the difficulties, it was possible to conclude the practical characterization work of biomass samples in the laboratory.

The topics discussed in this thesis justify further depth and dedication, and this work serves to open a range of possibilities for future research. The intention is to continue studying climate change and forest management models, mainly in identifying processes for the recovery of residual biomass to its full potential, but with a preferential focus on energy recovery through thermochemical conversion processes.

The conclusion of this work does not signify the end of the topics discussed, but rather the beginning of new research possibilities. Among the topics addressed, climate change will certainly be the impetus to continue research, analyzing its impact on the development of certain species through the establishment of growth models for invasive woody species. In addition, it is intended to establish a correlation model between the growth of certain woody species and parameters such as precipitation and temperature, which can serve as a model to characterize the climate in locations where data are not available.

The thesis proposes the continuation of the analysis of forest management models, mainly in identifying processes for the recovery of residual biomass to its full potential, but with a preferential focus on energy recovery through thermochemical conversion processes, such as torrefaction, pyrolysis, or gasification, combined with the analysis of forest-based supply chains, from a perspective of resource sustainability and the introduction of circular bioeconomy practices.

Keywords: climate change; forest management; invasive species; energy recovery; circular bioeconomy.

Indice

CHAPTER 1 – INTRODUCTION

Chapter Index

1.1. FRAMEWORK

The world faces a set of problems for which it has not yet envisioned a solution, namely, the impacts caused by environmental issues (Armaroli & Balzani, 2007; Mebratu, 1998; Wheeler & Von Braun, 2013). One example is climate change, which is a significant problem itself and also causes an important set of other problems (Adger, Huq, Brown, Conway, & Hulme, 2003; Deudney, 1990; Homer-Dixon, 1991).

It is undeniable that climate change is a reality that directly affects the daily lives of societies worldwide, since it is a global situation not just affecting a few insignificant people (Bandura, 1999; Scholze, Knorr, Arnell, & Prentice, 2006; Van Aalst, Cannon, & Burton, 2008; Wilshusen, Brechin, Fortwangler, & West, 2002). It is a planetary problem affecting everyone without regard to latitude or stage of development, but it is not caused by everyone individually at the same level of responsibility and intensity (Costello et al., 2009; Erwin, 2009; Hoegh-Guldberg, 1999; Huppert & Sparks, 2006; Parry, Rosenzweig, & Livermore, 2005; Tubiello, Soussana, & Howden, 2007).

Despite being a democratic phenomenon in its dispersion and consequences, it is also known that those who have less capacity to react and adapt will experience the effects of this new reality more intensely (Gibson, Ostrom, & Ahn, 2000; Schmidhuber & Tubiello, 2007). These people live in regions where climatic extremes are more directly felt, where water is scarce, or pests and disease outbreaks can appear and develop more persistently and frequently (Dercon, 2014; Dukes & Mooney, 1999; Giorgi & Lionello, 2008; Gregory, Johnson, Newton, & Ingram, 2009; Homer-Dixon, 2010; Trenberth, 2011; Wheeler & Von Braun, 2013).

Naturally, these will be the first inhabitants of Earth to suffer intensely from the damage caused by climate change, either directly through the occurrence of extreme weather phenomena or indirectly through the changes caused by the reaction of terrestrial systems to the new reality (Hallegatte & Rozenberg, 2017; Konisky, Hughes, & Kaylor, 2016; McBean, 2004; Wigley, 2009; Zanocco et al., 2018). For this reason, it is likely that many systems will not be able to adapt and evolve in the face of the new situation, most likely contributing to mass extinction of species and subsequent emergence of episodic invasion of ecosystems by other species, filling the void left by the extinction (Goss et al., 2020; Hertel & Rosch, 2010; Lambrinos, 2004; Patz et al., 2003; Sax et al., 2007; M. D. Smith, Knapp, & Collins, 2009; Strayer, Eviner, Jeschke, &

Pace, 2006; Tirado, Clarke, Jaykus, McQuatters-Gollop, & Frank, 2010; Vermeij, 1996).

In this scenario of a changing world, humans will have to adapt and evolve their daily activity, mainly with a view toward reaching a consensus to minimize the damage they have already caused (Lawler, 2009; Lejano, Tavares-Reager, & Berkes, 2013; Lucas, Leith, & Davison, 2015). That is, assuming the cause–effect relationship between anthropic activity and climate change as the binomial responsible for the situation we are currently experiencing, humans are the dominant species—the ones who can potentially suffer the most intense effects, and the ones who must work together and agree on two perspectives, described in the following paragraphs (Le Billon & Lujala, 2020; Shove & Spurling, 2013; Solecki, Leichenko, & O'Brien, 2011).

The first perspective is that, if it is not possible to quickly reverse the situation, then there is a need to contribute effectively to its reduction and mitigation, since it is not expected to be possible to counteract the current trend in a short period of time (Galatowitsch, Frelich, & Phillips-Mao, 2009). The difficulty we see in reaching a consensus, when everything would indicate the contrary, is due to human nature with our constant search for power and wealth, almost always neglecting future survival, since the risk does not appear to be immediate (Refsgaard et al., 2013). In other words, the thought continues to proliferate that there is still time, and all that remains is to determine how much time.

The second perspective is the need to change the energy paradigm on a global scale, which is considered the leading cause contributing to the occurrence of climate change, as will be seen in the course of this work. Although isolated measures are always valid, such as the use of renewable energies on a small scale or personal projects, they are insufficient; in reality, they contribute little to the overall mitigation of carbon dioxide emissions (Schaeffer et al., 2012). The decisive step toward replacing fossil fuels still seems far from realization, since alternative solutions have not yet demonstrated the ability to be precisely this: functional, available, and efficient alternatives (Farah & Tremolada, 2015; Gundlach & Stein, 2020; Höök & Tang, 2013; Pierce, 1984).

In fact, the largest problem for humans is the need for energy, which has been created by becoming dependent on it for the accomplishment of almost all daily tasks (Cornell et al., 2013; Hanjra & Qureshi, 2010; Karl & Trenberth, 2003; Moser & Dilling, 2004; Rasul & Sharma, 2016; Shove & Walker, 2014). The excessive dependence on transport and technological equipment in industrialized and developing countries makes this dependence even define the degree of autonomy and independence of a country vis-à-vis the outside world (De La Peña, Guo, Cao, Ni, & Zhang, 2022; Deutch, 2005; Hogan, 1975; Katinas, Markevicius, Perednis, & Savickas, 2014; Mara, Nate, Stavytskyy, & Kharlamova, 2022; Novak, 2015; Sattich, Morgan, & Moe, 2022; Sokołowski & Heffron, 2022). Examples include frequent military and diplomatic conflicts over oil, natural gas, or coal (Ali & Abdellatif, 2015; Fischhendler & Nathan, 2014; Keil, 2014; Leder & Shapiro, 2008; Monge, Gil-Alana, & de Gracia, 2017).

This economy, which is based on carbon, has led humanity to a path marked by the development of conditions of comfort, although with accentuated asymmetries, which has allowed a state of civilizational evolution to be reached, mainly after the industrial revolution, capable of providing better living conditions for a significant percentage of the world's population (Dorian, Franssen, & Simbeck, 2006; Pehlivan & Demirbas, 2007; Shi, Chai, Lu, Zheng, & Wang, 2022; Wu & Chen, 2018). However, environmental issues have arisen related to the continuous and intensive exploration and use of fossil energy resources, of which oil, coal, and natural gas stand out, responsible for releasing greenhouse gases (GHG) and carbon dioxide, and causing the greenhouse effect (Li et al., 2020; Nguyen, Hermansen, & Mogensen, 2010; Ruether, Ramezan, & Balash, 2004).

A news article published on the ZAP news site, 7 May 2015, citing the LUSA Agency, reported that "*the concentration of carbon dioxide (CO_2) in the atmosphere reached a record level in March, showing another clear sign of the global warming, with the monthly average global concentration of CO_2 in the atmosphere for the first time surpassing the level of 400 ppm*", according to information provided by the North American Agency for the Oceans and the Atmosphere (NOAA) (available at [Link], accessed on 26 June 2022).

In this same news item, the principal scientist responsible for monitoring greenhouse gases at NOAA, Pieter Tans, emphasized that "*this was a matter of time, as the measurement stations in the Arctic, in the Spring of 2012, and in Hawaii, in 2013, had already signaled that 400* *ppm had been exceeded. Now, reaching 400 ppm in the whole world makes the fact very significant".*

Tans also stated that *"until the industrial revolution and the massive use of fossil energies, the rate of CO_2 in the atmosphere has not exceeded 300 ppm for at least 800,000 years, according to studies on polar ice. This fact shows that the combustion of coal and oil caused an increase of more than 120 ppm in CO_2 concentrations since the pre-industrial era, half of which since 1980".*

Despite not being the only GHG responsible for climate change, given its abundance and percentage increase compared to conditions before the industrial revolution, it is likely the main cause of the current anomalies (Ciais et al., 2014; Hansen et al., 2013; Hoegh-Guldberg & Bruno, 2010; Houghton, 2009; Ledley et al., 1999; Ruddiman, 2003; Wuebbles & Hayhoe, 2002).

On the same day as the abovementioned article was published, the International Energy Agency announced on the VISÃO website that *"the increase in world CO_2 emissions from the combustion of fossil energies had stopped in 2014 when it stabilized at the 2013 level, but stabilizing the rate of greenhouse gas emissions is insufficient to stop climate change"* (available at [Link], accessed on 26 June 2022).

In the opinion of James Butler from the NOAA, *"it would take about 80% of CO_2 emissions from fossil fuel combustion to be eliminated to stop the increase in CO_2 in the atmosphere, as concentrations will not start to decrease until further reductions are made, drastic changes in CO_2 and, even after that, the decrease in concentrations will be slight".* To support this information, the scientist cited NOAA data, which showed that the average increase in CO_2 concentrations in the atmosphere was 2.25 ppm per year from 2012 to 2014, the highest rate ever recorded for three consecutive years.

For these reasons, it is now widely accepted that it is essential to reduce carbon dioxide emissions, and statements of this by senior officials, mainly politicians, are frequently reported in the media. In some cases, highly restrictive measures are announced, for example, a definitive ban on the use of coal for energy production.

This type of action has also reached Portugal, when the Minister of the Environment at the time, João Pedro Matos Fernandes, declared on in an interview with the television channel SIC NOTÍCIAS, 16 November 2017, that *"Portugal will stop produce electricity using coal by 2030 (...)"*, which was confirmed by the closure of the country's two coal-fired thermopower plants in 2019 and 2020 (available at [Link], accessed on 26 June 2022).

These statements, made in Bonn, Germany, when the Minister for the Environment was participating in the Climate Summit, were later repeated and confirmed in several situations, even by Prime Minister António Costa himself, who in his official TWITTER account wrote on 12 December 2017, *"we commit to abolish the production of energy from coal by 2030 and to encourage companies to reduce their use"* (available at [Link], accessed on 26 June 2022).

However, in reality, it will be a challenging objective to meet if the paradigm of electric energy production is not changed. As proof of this difficulty, the consumption of coal in 2017, according to a report in the newspaper PÚBLICO on 15 June 2018 by journalists Luís Villalobos and Ana Brito, rose *"71% compared to 2016, reaching 444 million Euros"* (available at [Link], accessed on 26 June 2022).

It is a trend that has been confirmed recently, with few exceptions. The growing need for more energy, mainly from the industrial sector, perhaps fueled by the economic growth after the end of the Troika period, led to growth in coal consumption by the two existing thermoelectric plants in Portugal, specifically, the Central Sines owned by EDP and the Pêgo Power Station owned by Tejo Energia, which consumed around 5.5 million tons of coal, imported from origins as diverse as Colombia, Venezuela, and South Africa (available at [Link], accessed on 26 June 2022).

Despite the need to satisfy this growing electricity demand, it seems that the path is set toward decarbonization of the economy. As mentioned above, policymakers continue to refer to this as a given, despite the permanent warnings that come from sources involved in the sector, such as the one by Ana Batista in the economic newsletter DINHEIRO VIVO, 11 January 2016. The head of ENDESA, Nuno Ribeiro da Silva, stated that *"for this to happen, more gas-fired combined cycle power plants must be used, and gas in Europe is not as cheap as in the US. It is more expensive* *than coal. Producing 1 MWh with gas costs 70 dollars and coal costs 40 to 45 dollars"*.

Now, can Portugal cope with only renewable energy? The answer may seem obvious, but the arguments raised by defenders of the continuity of coal and by defenders of the exclusive use of energies from renewable sources can both be valid. For example, in the abovementioned DINHEIRO VIVO piece, an argument is presented to justify the importance and necessity of using coal, in addition to what has already been presented and related to the cost of production. That is, *"despite Portugal being in on renewables, for them to produce all the national consumption, it was necessary to have even more wind farms and dams and solar plants (than those necessary to supply the entirety of the need). Because the weather is unpredictable, a coal-fired power plant is one of the most predictable"*. In other words, with renewable energies as the only energy source for the country, Portugal runs the risk of not having the infrastructure capable of meeting its needs, when it is not possible to produce power by using wind, sun, or water resources.

On the other hand, arguments point in the direction of the environmental advantages, highlighting the reduction in greenhouse gas emissions and the contribution to the mitigation of the phenomenon of climate change. These tend not to reference arguments of an economic nature, where coal has an advantage, including the use of natural gas (Christophers, 2019; Jewell & Cherp, 2020; Mac Dowell, Fennell, Shah, & Maitland, 2017; York, 2012). Any one of these renewable energy sources suffers from the same disadvantage, since they all depend on the weather conditions and can fail at any time, with a change in the standard conditions of sun exposure, intensity and direction of the wind, or precipitation (Das, Mathur, Bhakar, & Kanudia, 2018; Notton et al., 2018; Perez-Arriaga & Batlle, 2012).

As mentioned above, there may always be a need to overcome the lack of energy in periods when it is not possible to use renewable sources (Aflaki & Netessine, 2017). For these situations, either due to the absence of energy production or due to the occurrence of unexpected consumption peaks, the electrical network must be supported by backup units, which can be activated when needed and respond quickly and in sufficient quantity to meet demand (Liebensteiner & Wrienz, 2020).

Here, biomass power plants can play an important role, since as part of the renewable energy segment, they can be an alternative to coal-fired production units (Romanelli, 2016). In addition, in some situations, there may be the possibility of converting coal-fired units to biomass, guaranteeing the continuity of energy supply and ensuring supply at critical times (Steinke, Wolfrum, & Hoffmann, 2013).

However, the use of biomass is also not without problems, as it depends on a natural resource in permanent evolution, which will most likely be influenced by climate change (Jiang, van der Werf, van Ierland, & Keesman, 2017). From this perspective, climate change influences forest development and evolution and will determine whether the resource remains unchanged or if it transforms and acquires new characteristics (Trainer, 2013). For example, the diversity of forest species in a given region may change through the replacement of some species by others more adapted to the new circumstances; even if they are autochthonous, novel species may migrate from other regions where the soil and climate conditions are similar to the new reality (Field, Campbell, & Lobell, 2008). Alternatively, the new conditions may allow and even encourage the replacement of native species by exotic species, which may show invasive behavior (Séférian, Rocher, Guivarch, & Colin, 2018).

These changes in the forest cover will occur, and this should be analyzed beyond the problem of the loss of biodiversity, since the economic questions arising from the exploitation of the natural resource will undoubtedly first be felt by the populations that depend directly on the forest and its resources (Moreira, 2006).

An example of this is the dispersion of exotic species, such as acacias, in areas that were traditionally occupied by native species and that provided some income. For example, there were areas of oaks that provided good quality wood for the furniture industry, areas of stone pine that supplied pine nuts, or even areas with different species that were used to produce honey. Now, they are fully covered by acacias and no longer provide any benefit (Ziska, Blumenthal, Runion, Hunt, & Diaz-Soltero, 2011).

The increase in the probability of the occurrence of forest fires can also be associated with the phenomenon of climate change, since there is a tendency for the emergence of favorable conditions for the occurrence of fires, namely, the increase in periods of drought combined with the increase in fuel load due to the invasion of exotic species (Hobbs & Mooney, 2005).

The combination of these factors, together with others of a demographic and cultural nature, increases the risk of fires that destroy forest heritage. Therefore, it is a subject that arouses the interest of those who work and investigate the issues related to the development of the forestry sector; Portugal could experience—in a relatively short time—profound changes in this important sector of its economy (Arianoutsoua & Vilà, 2012; Marchante, Marchante, & Freitas, 2003; Vicente et al., 2013).

This is the motive for innovative research to assess the impact of climate change on the forest while relating this phenomenon to other forest-change factors, for example, the expansion of invasive species, which greatly benefit from a post-fire situation, since, owing to their heliophilic behavior, they quickly occupy open gaps, preventing the recovery of other species. This research also presents and discusses newly adapted forest management models, which will take into consideration new variables for the current scenario.

1.2. Research Problem

To serve as a basis for the present research, there is a set of framing questions that are answered by addressing the objectives outlined and presented in the following section.

For the various reasons addressed in the previous section, this is an innovative investigation, which introduces new evidence to allow a better understanding of these phenomena.

The framing questions follow:

- How is climate change causing variations in environmental conditions and influencing the evolution of the Portuguese forest?

- Considering the dispersion of invasive species as one of the consequences of climate change affecting the forest, could the energy recovery of these species be a solution for sustainable control and eradication actions?

- What challenges may the Portuguese forest face in the future, namely, concerning management models and resource valorization?

1.3. Objectives, Methodology, and Motivation

The objectives aim to answer the questions presented above, namely, to understand the interconnection between climate change and the changes in the national forest from an environmental perspective while determining the evolutionary direction and adaptiveness of the forest as a living and dynamic resource.

It is imperative to understand the current state of the Portuguese forest, including its existing species, both native and alien, with particular emphasis on the latter since alien species are beginning to play a very significant role both in the area occupied and their influence on, for example, fire-risk scenarios, given the fuel load they represent.

It is also important to systematically analyze the energy potential of the existing species, create a comparative map, and study the potential for using energy recovery of alien species considered invasive, to verify the hypothesis of its control through pressure on the resource and the creation of a value chain.

Finally, it is important to develop a model of forest management dedicated to energy based on autochthonous species and defending native biodiversity, where different perspectives of value-chain creation are mixed by the overlapping of traditional economic practices.

Research methodology comprises the general framework used in the study, the paths followed, and the techniques used. From a more practical perspective, the research methodology considers the concrete methods used to understand the realities analyzed in the research (Kothari, 2004; Steglich, Snijders, & Pearson, 2010).

The design or model of an Investigation is the plan that guides the researcher in collecting, analyzing, and interpreting data and observations, and allows conclusions to be drawn concerning the topic under investigation (Steglich et al., 2010).

Quantitative and qualitative research methods are based on different assumptions that shape the research objectives, the roles assumed by the researcher, and the relationship the researcher maintains with other participants in the research (Cavana, Delahaye, & Sekaran, 2001; Jick, 1979; Reinhardt & Cook, 1979).

The qualitative method differs from the quantitative method due to the different data collection methods. A qualitative methodology is concerned with analyzing and interpreting deeper aspects of data, providing a more detailed analysis of investigations, habits, attitudes, and behavior trends, among other aspects, highlighting the richness of a qualitative approach (Denzin & Lincoln, 1994; Jick, 1979; Patton, 1990).

A qualitative investigation is not defined simply by choosing specific methods. There must also be a precise understanding of the relationship between the topic studied and the method chosen (Mack, Woodsong, MacQueen, Guest, & Namey, 2005); namely, the research questions must be clearly formulated to reduce the risk of the researcher not gathering the relevant data for analysis. Case studies are often associated with qualitative analysis methods (Erickson, 1985; Jick, 1979), which is the main reason for the choice of a qualitative approach in this research.

Case studies are an increasingly popular and relevant research strategy, although there are several challenges in conducting case studies as they are time-consuming and the conclusions may not be generalizable if the results obtained are ambiguous or raise some difficulty in interpreting the final results (Sultan & Yin Wong, 2013; Yin, 2009, 2015).

Building theories from case studies is a research strategy that may involve using one or more cases (J. A. Smith, 2015). Individual case studies are appropriate when the case is for a specific reason, which may occur when the case provides a critical test for a well-established theory or when the case is extreme, unique, or has a special aspect to reveal (Strauss & Corbin, 1994).

The case study approach can also incorporate multiple case studies. However, at a certain point, it will no longer be possible to investigate cases intensively; therefore, depending on the available resources, the fewer the case studies, the greater the opportunity for deeper observation (Merriam, 1998).

The analysis of a case study combines different data collection methods, such as archives, interviews, questionnaires, and observations, depending on the type of framework. The most common sources of evidence used in developing case studies are documentation, archives, interviews, observation (direct and participant), and physical artifacts (Perren & Ram, 2004). Compared to other methods, one of the virtues of case studies is that it allows the collection of evidence based on various sources (Yin, 2009).

Thus, after defining the case study, it specificity and nature should be determined. Knowing the importance for and reasons underlying each subtheme is also relevant to determine the added value, the information that will be collected, and its impact on fulfilling the desired outcomes. For this purpose, and for each subtheme, an extensive review of the existing literature was carried out, which enabled understanding the knowledge related to the subject under analysis.

The tasks to be carried out during this project follow:

- Task 1. Bibliographic research and framing of the theme.
- Task 2. Characterization of the effects of climate change on mainland Portugal.
- Task 3. Statistical analysis of the parameters "air temperature" and "rainfall" to confirm the trend series, determining the occurrence of climate change.
- Task 4. Characterization of invasive woody species in the Portuguese forest and their distribution and geographic dispersion.
- Task 5. Correlation between climate change/fires and dispersion and propagation of invasive forest-type species.
- Task 6. Characterization of the physical and chemical parameters of the invasive species that justify their energy recovery in comparison with native species (shrubs/trees) traditionally used for biomass for energy purposes.

- Task 7. Dendrometric characterization of invasive species selected for this investigation, specifically *Acacia dealbata*, within a target area in Casal do Rei (União de Freguesias de Cabeça e Vide, municipality of Seia) to define a growth model for the species.

- Task 8. Identification of the best technologies currently available for biomass energy recovery, considering the results obtained in the energy characterization of the species under analysis.

- Task 9. Analysis of the energy potential of the different heliophilous species found in the area selected for this study.

- Task 10. Comparative analysis of the potential for energy recovery from the main invasive species found in the area selected for the present study with the species traditionally used to produce fuels derived from biomass, namely, the production of biomass pellets.

With climate change considered a concrete situation and responsible for several widely reported changes, it is also expected that the forest, as a living resource, will react and evolve to a new condition.

From this perspective, it is likely that some alien species already abundant in the Portuguese forest may become territorially dominant, especially in areas of the country where climate change has greater impact.

With the increase in the area occupied by these invasive species, the fight to eradicate them, which started a few years ago but without significant success, will become even more difficult. As an alternative to traditional control, the solution is presented for recovering energy from this source of biomass, which can be seen as an alternative to other species. This increasing pressure caused by their use as fuel or raw material will mitigate their expansion.

The personal motivation for this work comes from several years of professional experience in producing solid fuels derived from biomass, namely, the production of biomass pellets and biomass torrefaction, thus aiming to acquire technical skills in forestry and ecology.

The personal objective is to develop a sustainable environmentally consistent model of forest management based on native species by creating a value chain that allows the use of forest products to produce energy. Simultaneously, temporal continuity is created in the development of the forest, perpetuating its use for future generations.

This work aims to be an innovative contribution through the description and analysis of the case study and the presentation of concrete possibilities to improve the existing situation, namely, the replacement of traditional fuels used for the generation of thermal and electrical energy. Furthermore, at the socioeconomic and environmental level, related issues of job creation and the impact of biomass exploitation for an energy source are also important.

1.4. Organization of the Manuscript

The present work was developed according to the model of a collection of articles, consisting of 12 publications, distributed according to the data shown in Table 1.1.

Table 1.1. Distribution of the articles included in the present study according to the journal, its quartile, and the respective scientific area (information collected on https://www.scimagojr.com/journalrank.php, accessed on 15 May 2022).

No. Of articles	Journal	Quartile	Scientific area
2	Forests	Q1	Forestry
2	Climate	Q3	Atmospheric Science
4	Environments	Q2	Environmental Sciences
1	Resources	Q2	Natural and Landscape Conservation
1	Fire	Q1	Environmental Science
1	Plants	Q1	Ecology
1	Recycling	Q2	Waste Management and Disposal

These journals were selected for the submission of articles based on the following criteria:

- All journals are indexed in the SCOPUS database;
- All journals are open access (MDPI;
- All journals, except one, are Q1 and Q2.

In the case of the journal Climate, despite being Q3, it was decided to proceed with submission, since the articles submitted to this journal are not specifically about climate or climate change but rather about the effects climate change can have on forests or how forests can contribute to climate change mitigation.

In this way, the articles were elaborated, not following the structure now presented in the index of this work but rather following the order in which the data were collected. This sequence of data acquisition and production of articles also followed the demand and the need of the candidate to increase knowledge on the topics covered in this work. Therefore, this work is organized as follows:

CHAPTER 1. INTRODUCTION: This chapter is divided into five sections. The first section (1.1) corresponds to the framework of the theme addressed in this work. In this framework, a brief characterization of the problem is given, moving from a global to a national scale. The second section (1.2) presents the problem under investigation, with the presentation of the questions to be addressed during the investigation. Paths for the answer/solution/mitigation of the identified questions are indicated. The third section (1.3) presents the objectives of the present work, along with the methodology used and the reasons that led the candidate to address these issues in this work. The fourth section (1.4) describes the organization of the manuscript. Finally, the fifth section (1.5) presents the bibliographic references used in Chapter 1.

CHAPTER 2. FRAMEWORK: This chapter analyzes the different theoretical aspects and the current state-of-the-art on the topic (and subthemes) under investigation through a literature review, divided into four sections. The first section (2.1) presents a bibliographic review article entitled *"Historical Development of the Portuguese Forest: The Introduction of Invasive Species"*, which summarizes the evolution of the

Portuguese forest through time, culminating in the recent introduction of invasive species, in particular, *Acacia dealbata*. The second section (2.2) presents a bibliographic review article entitled *"Socioeconomic Aspects of the Forests in Portugal: Recent Evolution and Perspectives of Sustainability of the Resource"*, which analyzes the forest as a resource and its importance for the national economy. This article categorizes the different aspects related to the use and valorization of the forest resource and its evolution through time, along with the direction of future development. The third section (2.3) presents an article entitled *"The Evolution of Climate Change in Portugal: Determination of Trend Series and its Impact on Forest Development"*, which analyzes the change in climate and its impacts on Portugal's forests. In this article, based on historical data related to the average monthly air temperature and the average monthly precipitation, trend lines are defined to understand the expected course for the development and evolution of the basic climatic conditions for the Portuguese continental territory. The fourth section (2.4) presents a review article entitled *"Forest Contribution to Climate Change Mitigation: Management Oriented to Carbon Capture and Storage"*, which analyzes the contribution and role of forests to climate change mitigation.

CHAPTER 3. Spread of Invasive Species: This chapter addresses how invasive species benefit from processes associated with climate change, namely, the proliferation of rural fires. Thus, the first section (3.1) presents an article entitled *"The Impact of Rural Fires on the Development of Invasive Species: Analysis of a Case Study with Acacia dealbata in Casal do Rei (Seia, Portugal)"*, where the role of fire as an agent of species selection is analyzed, highlighting the area selected for the present investigation. The second section (3.2) presents an article entitled *"Fire as Selection Agent for the Dissemination of Invasive Species: Case Study on the Evolution of Forest Coverage"*, which analyzes the role of fire as a facilitator of the dissemination of some invasive species, such as *Acacia dealbata*. The third section (3.3) presents an article entitled *"Allometric, Growth, and Biomass Estimation Models for Acacia dealbata: a Case Study in Serra da Estrela Natural Park (Portugal)"*, which presents a set of growth equations, allometric models, and estimation of the amount of biomass produced by the species *Acacia dealbata*, based on an analysis of data collected in a stand of the species located in Casal do Rei (Seia, Portugal).

CHAPTER 4. CONTROL OF INVASIVE SPECIES: This chapter is divided into two sections and addresses the possibility of energy recovery from *Acacia dealbata* to create a value chain that enables the sustainability of control and eradication actions. Thus, the first section (4.1) presents an article entitled "*Energy Recovery from Invasive Species: Creation of Value Chains to Promote Control and Eradication*", which analyzes the possibility of using residual biomass from operations to control and eradicate *Acacia dealbata* in energy recovery processes. The second section (4.2) presents an article entitled "*Acacia dealbata Aboveground Biomass Assessment: Sustainability of Control and Eradication Actions to Reduce Rural Fire Risk*", which presents a methodology for the quantification of the aboveground biomass generated by the stands of *Acacia dealbata*, to optimize the logistical processes associated with the control and eradication of this species.

CHAPTER 5. ASSESSMENT OF THE IMPACT ON FOREST MANAGEMENT MODELS ON THE ENERGY RECOVERY POTENTIAL AND THE PROVISION OF ECOSYSTEM SERVICES: This chapter is divided into three sections, presenting a set of three articles, where the application of the assumptions in the present work was analyzed to answer the questions presented above. Thus, the first section (5.1) presents a bibliographic review article entitled "*The Impact of Climate Change on Forest Development: A Sustainable Approach to Management Models Applied to Mediterranean-Type Climate Regions*", with a discussion about the impacts. The second section (5.2) presents an article entitled "*Control of Invasive Forest Species through the Creation of a Value Chain: Acacia dealbata Biomass Recovery*", which assesses the potential for energy recovery from biomass. The third section (5.3) presents an article entitled "*Carbon Sequestration Potential of Forest Invasive Species: A Case Study with Acacia dealbata*", which analyzes the aspect of ecosystem services through the ability of *Acacia dealbata* to capture and sequester carbon.

CHAPTER 6. DISCUSSION AND CONCLUSIONS: This chapter is divided into six sections. The first section (6.1) discusses the results obtained in regard to the relationship between climate change and invasive species. The second section (6.2) discusses the control of invasive species and the creation of value chains. The third section (6.3) analyzes the perspectives for developing forest management models in the face of the new assumptions and scenarios. The fourth section (6.4) presents the conclusions. The fifth section (6.5) presents the limitations and difficulties encountered during the execution of the research project. The sixth section (6.6) presents prospects for future work.

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CHAPTER 2 – Framework

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forests

Review

Historical Development of the Portuguese Forest: The Introduction of Invasive Species

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Abstract: Portugal is a country with a territorial dimension of approximately 90,000 km^2. However, the forest occupies a prominent position, since it represents about 35% of the total area of the country. Portuguese people always had a very close connection with the forest, which has provided the necessary resources for the development of its communities. The geological substratum of continental Portugal is very old and may therefore have witnessed the evolution of its plants, from the early beginning to the present time, as well as all sort of historical and environmental landmarks such as glacial periods or mass extinctions. Also, from the perspective of human occupation, Portuguese territory was crossed by hunter-gatherer populations who, initially, were constantly moving and looking for sustenance, but at a later stage, chose to settle. This relationship between human populations and the forest is, thus, very old and demonstrates the interdependence between the subsistence of the populations and the resources exploitation. Currently, the main national economic groups are based on forest industries, which depend directly on the exploitation of the three dominant species, *Eucalyptus globulus* Labill., *Pinus pinaster* Aiton and *Quercus suber* L., demonstrating the human role in the development of the forest, motivated by the satisfaction of its needs. This work reviews the historical development of the forest in mainland Portugal, from geological times to the present, including the arrival of exotic species that later acquired invasive behaviors and now occupy significant areas of the national territory.

Keywords: forest management; forest development; invasive species; forest economy

1. Introduction

The widespread opinion of the Portuguese people is that the national forest is composed of a monoculture of eucalyptus that dominates more land than any other species. Important economic interests support eucalyptus plantations, ensuring the supply of raw materials for one of the most important industrial activities in the Portuguese industrial landscape: pulp and paper production. Thus, despite high-water consumption, soil erosion and depletion, reduced biodiversity, and increased difficulty in controlling rural fires, eucalyptus plantations continue to have defenders. According to the results of the National Forest Inventory [1], eucalyptus plantation area grew continuously in the last two decades, and is today the dominant species in Portuguese forests, covering more than 800,000 hectares [2]. As such, it is important to understand how forests evolved in Portugal to the current situation, with approximately 75% of its area occupied by a limited number of species, dominated by eucalyptus, maritime pine, and cork oak.

Forest is a fulcrum for the national economy, in addition to its immense weight from the environmental perspective, as a guarantor of biodiversity and as a social framework for hundreds of thousands of Portuguese people living in its vicinity. This perspective, probably outside the everyday thinking of the majority of the Portuguese people, can easily change, simply by introducing a simple fact into the discussion, namely: "the forest is fundamental for three of the largest national companies." In fact, it does not take much effort to understand that in reality the cork–paper–wood triad has a very significant weight in the national economy, as will be shown in another section.

Beyond these three giants of national industry, there are many other economic activities dependent on raw materials from forestry sector, some even older than those highlighted in the previous paragraphs. These include the furniture industry, which had a great expansion in the northern part of the country; the artisanal shipbuilding industry, especially in some coastal ports, where traditional fishing activities had a great role in local economy; and the cooperage industry, spread throughout the country, since wine production extends from north to south. Some of the other traditional forest-dependent activities, have unfortunately been lost due to the advance of time and the option of using different modern raw materials.

Forests are not solely a provider of wood. The exploitation of other by-products, and even the space itself, allows the development of a significant set of other economic activities that lead to entire populations taking their livelihood directly from the forest through the practice of various economic activities, while others can enjoy the space in the activity of leisure and in conviviality with nature. Examples include the production of nuts, such as walnuts, chestnuts, hazelnuts, and almonds; apiculture, which in addition to producing honey contributes to the pollination of different crops; the picking of mushrooms and wild fruits; or the husking of oaks for the extraction of tannins for the leather industry.

However, perhaps the forestry sub-sector with the greatest industrial tradition is the extraction of resin and the production of rosin derivatives. There remain some large industrial units still in operation, although resin extraction has practically been abandoned, since there are only a few points in the country at which it occurs. Currently, this industry resists the importation of gum, from which pine rosin derivatives are extracted.

In spite of the importance of the forest in its various aspects, in particular the economic and environmental components, it seems that it is still not given due attention. Its exploitation and management, with honorable exceptions, continues to be undertaken in an uncoordinated manner and, as previously mentioned, with one-off measures not based on long-term policies or a perspective of future sustainability.

The main objective of this review article is to analyze the evolution and development of the forests in Portugal, while providing a historical perspective. The present work provides a historical review of the development of the forest in the territory of mainland Portugal, encompassing the geological and the historical period, from the arrival of the humans, until present time. Then, a historical analysis of the arrival of some exotic species and its invasive behavior, namely, acacias and eucalyptus, is also made.

2. Characterization and Evolution of the Forest in Portugal

2.1. From the Early Beginning to the Arrival of Humans

Mainland Portugal is based on a geological substratum so old that all the steps of the evolution of terrestrial plants can be verified here, since there is terrain in Portugal that dates back to the Paleozoic Era (541.0–251.90 Ma). During the Ordovician period (485.4–443.8 Ma), plants occupied the continents, but the first fossil records of the oldest terrestrial plants were dated to the Silurian period (443.8–419.2 Ma). During the Devonian period (419.2–358.9 Ma), trees arose and, consequently, forests. In the Carboniferous (358.9–298.9 Ma) and Permian (298.9–251.9 Ma) periods, forests developed considerably, producing large volumes of biomass that became the source of extensive deposits of coal [3].

During the Mesozoic Era (251.90–66.0 Ma), forests were mostly composed of ferns and conifers. In the Jurassic period (201.3–145 Ma), plants with flowers appeared. In the angiosperms, the seeds stopped being protected by a fruit [3,4].

In the Tertiary Period (66.0–2.58 Cenozoic Era), the climate on the Iberian Peninsula was diverse enough to allow for the proliferation of different types of flora adapted to different environments. For example, coastal areas were covered by mangroves, but species of *Arbutus*, *Cistus*, *Chamaerops*, *Nerium*, *Olea*, *Pistacia*, *Phillyrea*, *Rhamnus*, and *Milax*, and other species of *Quercus*, *Juniperus*, *Dracaena*, and *Olea* were also present. *Pinus* arose primarily to occupy the space left available after occurrences such as fires, tree death, or landslides. This substitution of species was facilitated by the climatic changes that occurred in the Middle Miocene, corresponding to the Languian (15.97–13.82 Ma) and Serravallian (13.82–11.63 Ma) that caused the extinction of the species characteristic of the tropical and subtropical forest regions [3,5].

During the Miocene epoch (23.02–5.333 Ma), most of the territory of the Iberian Peninsula was subjected to a tropical climate, which promoted the proliferation of extensive forests mainly consisting of laurel species (or laurissilva species), but also of species belonging to families that are currently only found naturally in the tropical, temperate or subtropical regions of the Northern Hemisphere, but are now extinct in the Iberian Peninsula [3,5].

In the Pliocene Age (5.333–2.58 Ma), the Mediterranean climate was the dominant form, where, through adaptive radiation processes, new species emerged, many of which were adapted to fire. The common genera of the current flora diversified and organized the most common plant communities in the Iberian Peninsula, such as forests with evergreen species, thick forests with broad and lustrous hard leaves, and communities of aromatic limestone plants. At this stage, grasses expanded through spaces previously occupied by tropical and subtropical species, creating savanna areas [3,5].

In the Quaternary Period, which began 2.58 million years ago, more precisely in the Pleistocene Epoch (2.58–0.012 Ma), a series of glacial cycles occurred, with periods of approximately 100,000 years interspersed with warmer and wetter interglacial periods of about 10,000 years. In the colder periods, most tree species occupied more coastal regions, forming complex associations of arboreal, shrub, and herbaceous vegetation, whereas in the innermost regions, small wooded steppes occupied most of the territory [3,5].

The elements of tertiary tropical and subtropical origin that were more susceptible to temperature variations survived these profound climate changes in some hot, low-lying places near the coast, in deep valleys, in escarpments exposed to the sun, or in very specific lithologies. Some relics of these species are still present in continental Portugal, such as *Ilex aquifolium* L. (Figure 1), *Buxus sempervirens* L., *Prunus lusitanica* L. (Figure 2), *Laurus nobilis* L., *Myrica faya* Aiton or *Taxus baccata* L., but also shrub species such as *Arbutus unedo* (Figure 3), *Olea europaea* var. *sylvestris* L., *Phyllirea media* L., *Viburnum tinus* L., *Myrtus communis* L., and *Rhododendron ponticum* subsp. *Baeticum* L. [3,5,6].

During the Holocene (0.012 Ma), the increase in temperature and precipitation caused a widening of the area occupied by forests to mountains and interior regions. In this period, the steppes of junipers and pines, so common at the end of the Pleistocene, were replaced by forests of oaks, holm oaks, birch trees, pines, and junipers, creating a predominantly forested landscape interspersed with clearings composed of shrub and herbaceous species. These landscapes were formed by the occurrence of forest fires, trampling of plants by large wild herbivores, landslides, floods, strong winds, and falling trees.

Figure 1. *Ilex aquifolium* from Margaraça (Arganil, central Portugal).

Figure 2. *Prunus lusitanica* from Margaraça (Arganil, central Portugal).

Figure 3. *Arbutus unedo* from Margaraça (Arganil, central Portugal).

2.2. *Influence of Humans on Forest Development*

Human populations also impacted the spread of shrub and herbaceous vegetation areas, increasing the pasture areas available for large wild herbivores, concentrating them in certain places of easier access, creating protection zones around the camps, facilitating the visibility of those who were on watch, and facilitating the growth of shrub and herbaceous species of interest to collectors. This led to the replacement of natural ecosystems with semi-natural ecosystems, such as meadows, and other agro-ecosystems, such as fields with agricultural crops [3,5,7,8].

In the sixth millennium BCE(Before the Common Era), the Neolithic period began with the arrival of small itinerant agro-pastoral groups from the eastern Mediterranean in the Portuguese territory, contemporized with the last groups of hunter-gatherers who inhabited the territory. When the soils were depleted, these populations sought another place and repeated the process, abandoning the terrain, allowing its natural recovery [3,5]. However, this practice of opening fire clearings initially had good results and led to the flowering of meadows since the ashes served as fertilizer, but quickly led to the appearance of pyrophyte species with little value for animal feeding, simultaneously causing soil erosion and soil nutrient impoverishment [3,5,6].

During the fourth and third millennia BCE, in the Chalcolithic Age or the Copper Age, the effects of the actions of humans on the landscape significantly increased with the construction of megalithic structures and the settlement of populations, most probably directly associated with the strong connection of communities with agricultural practice and livestock. During this period, the substitution of forest species for other types of vegetation increased and important technological innovations appeared that allowed greater interventions within the environment. Examples of this include the appearance of the plow and the use of animal traction in agricultural work [3,5].

In the Bronze Age, which covered much of the second millennium BCE and the beginning of the first millennium BCE, new technological knowledge emerged, such as soil drainage and irrigation of crops, enabling in northern and central Portugal, at least, human settlement in areas of lower altitude with soils with qualities better suited to agriculture. This situation, which was intensified by the needs of ever-increasing communities and increased the ability to increase agricultural production, led to forests being far from communities to the detriment of the agricultural land surrounding the settlements. This increasingly extensive perimeter was essentially destined to serve as pasture for domestic animals [3,9,10].

In the Iron Age, the Portuguese territory was influenced by many different ethnic and cultural factors with the development of organized and structured societies (Figure 4). However, all these societies shared one aspect in common: mining and manufacturing of iron tools. This played a major role in forest development, since large-scale deforestation was initiated during this period, as large quantities of timber were needed for the production of charcoal, which later fueled iron smelting furnaces [5,11].

Figure 4. Reconstruction of a house of "Citânia de Briteiros" in Guimarães (Northern Portugal). It is one of the most important settlements of the so-called "Castro culture", with occupation from the Bronze Age to the Roman period. Upon the arrival of the Romans, the inhabitants of this "castro" and all others in the region were forced to leave the top of the hills and move to the much easier to control valleys. They were likely to have been reoccupied during the short period of the Arab invasion of northern Portugal, and then permanently abandoned.

The arrival of the Roman period brought enormous technological developments, the integration of local economies in a large global economic space, and the intensification of territory exploration. The Romans produced many agricultural innovations and introduced new species of plants. This period of economic development led to a period of forest regression [3,10,12,13].

At the beginning of the fifth century CE(Common Era), the presence of the barbarian tribes ended in this area with the Roman occupation that lasted more than five centuries. These peoples, who sought better locations to live, were most likely attacked by other migrating peoples, such as Huns and Slavs in their homelands. Climate change may also have prevented the cultivation of land. These barbarians began to reach the Iberian Peninsula during the period of Roman occupation.

After the fall of the Roman empire, these tribes took control of the peninsula, with the ruling power passing through several hands, depending on the dominant horde, transforming this period into a time of disorganization, leading to ruralization of society and dispersal of urban nuclei, and increasing pressure on natural resources. The economy of these barbarian peoples was based on semi-sedentary agriculture and cattle raising. The climatic cooling between 450 and 950 CE and the instability caused by barbarian invasions changed the way of life of the populations, allowing for the recovery of forests, with the reappearance of forests of birch and pine [3,13,14].

The Muslim invasion of the Iberian Peninsula occurred between 711 and 716. This invasion, with no major impact on the northern part of the peninsula, led the population to seek refuge in the abandoned "castros", the old uninhabited villages from the Iron age, at the top of mountains, leaving the lower and more fertile areas. This situation produced a pause in the regression of the forests in the north that only resumed with the Christian reconquest. In the center and in the south, this Muslim presence was more effective, significantly altering the way of life of the populations. These invaders brought with them new irrigation techniques and new agricultural crops, but also involved the use and exploitation of the forest, mainly to obtain wood for shipbuilding and housing. In this region, the forest continued its regression [3,13].

The Christian reconquest occurred in a period of favorable climatic conditions, namely, the Medieval Warm Period, which facilitated the development of agriculture in detriment of pastoralism, in response to the growing needs of an increasing population, but again causing regression of the forest area [3].

Military and religious orders played a decisive role both in the conquest of the territory and in its planning and stabilization. In the Middle Ages, rural spaces were enormously important, since they provided subsistence for populations and guaranteed the permanence of settlements in the conquered territories. There was also a need to occupy territories less suitable for agricultural purposes, such as marshy areas, to protect agricultural land from the advancement of dune fields in some areas of the coast, and, in parallel with the expansion of agricultural land, to occupy extensive forest areas, mainly in coastal areas such as Leiria (central Portugal) and Alentejo (south Portugal) [15,16].

The "montado", the cork oak traditional forest from the south of Portugal, resulted from the simplification of the forests of cork oaks and holm oaks, punctuated by other types of oaks, due to the grazing, cutting, and burning of trees and shrubs. The aim of these activities was to reduce the shading capacity and the density of the trees, eliminating the shrub species and promoting the occurrence of heliophilous herbaceous species. The growth and appearance of the "montado" was closely linked to the process of deforestation, creating a forest that was not completely natural [3,6,15,17]. The "montado" is not capable itself of guaranteeing the replacement of dead trees, even with low grazing intensities. When subjected to grazing without interruption, is converted into "pseudo steppes" devoid of trees, so that, since the Middle Ages, recommendations for reforestation were frequent [3,6,15,17].

The need to extend agricultural production to lesser soils and the lengthening of forest fire cycles in the mountains have accentuated erosion processes, filling large rivers with sediment drawn from slopes. The demographic increase and exhaustion of natural resources in the late Middle Ages led to an accumulation of crises and scarcity that greatly affected populations during the 14th century [3,6,18].

In the following centuries, the construction of different types of vessels for fishing, maritime trade, war, and, above all, for the construction of ships and caravels during the Portuguese maritime expansion period increased the demand for trees, with oak trees leading the list of the most sought-after for the construction of most types of vessel [19].

As was seen previously, the rulers demonstrated concern about the management and exploitation of forest areas, and this concern varied with the use of the forest throughout the different periods of the country's history. Due to the wood products crisis during the 16th century, the Law of the Trees was introduced in 1565, in the reign of King Sebastião, promulgated after the "Cortes" of Lisbon of 1562, and later transcribed in 1603 in the Philippine Ordinances [19,20]. In 1605, the "Monteiro-Mor" Regiment created the first inventory of the crown and pine forests and was one of the first diplomas that separated the pine forests by the two most common species: maritime pine and stone pine [20].

During the reign of King João V (1706–1750), deforestation significantly increased due to the increase in agricultural production. This situation was common in other countries in central and southern Europe, such as France and Germany, where the forestry sector was very important [20,21].

Significant progress occurred in Portugal as early as 1824 with the creation of the "Administração Geral das Matas do Reino", or the Kingdon Forests Management Survey [22]. Subsequently, the actions undertaken by the Forestry Services promoted the recovery of natural forests in some areas of the interior, along with the conservation of soil and water [23]. Construction of the railroad, which began in the mid-19th century, was another blow to the continent's depleted forest cover, with over 2000 km of railroad built in the last half of the century [20,24]. During this same period, the work of fixing and afforesting dunes in a large part of the Portuguese coast continued, due to the systematic and documented start of José Bonifácio de Andrada e Silva [21]. The afforestation of the mountains of the interior of the country was also undertaken [20]. Important changes occurred in the agroforestry space that led to the extension of the agricultural production area (production of cereals in the south and vineyards and olive groves all over the country) and an increase in forest area with reforestation of cork oak and pine [20].

Between 1874 and 1910, the forest area had an average annual growth rate of 37,614 hectares. The Agricultural and Forestry Charter of 1910 is the first and only source of information in which the agricultural, forestry, and uncultivated areas of the national territory were effectively documented [20,21,25]. The evolution of the forest landscape since the 19th century was characterized by a progressive occupation of uncultivated lands and expansion of pine forest area, which grew by approximately 1,800,000 hectares, mainly as a result of private initiatives [20].

Law no. 1971 concerning forest settlement was approved on June 15, 1938, becoming known as the Law of the "Baldios", common designation for the wasteland managed by local populations, and referenced the creation of a large natural park. This park, the Peneda-Gerês National Park, was created in 1971 after the publication of Decree-Law no. 9/70 of June 19, 1971 [20,25].

The 1950s were a turning point for forestry in Portugal. From 1956 to 1964, the forests were most heavily forested, with 270,000 hectares planted in 1970. In 1972, planting comprised 297,641 hectares in the mountains and 8,255 hectares in the dunes, representing just over half the area originally planned. The most widely used species was *Pinus pinaster* (Figure 5). Considerable effort was made to create a road network fundamental to the economic exploitation and defense of forest stands [20,21,26].

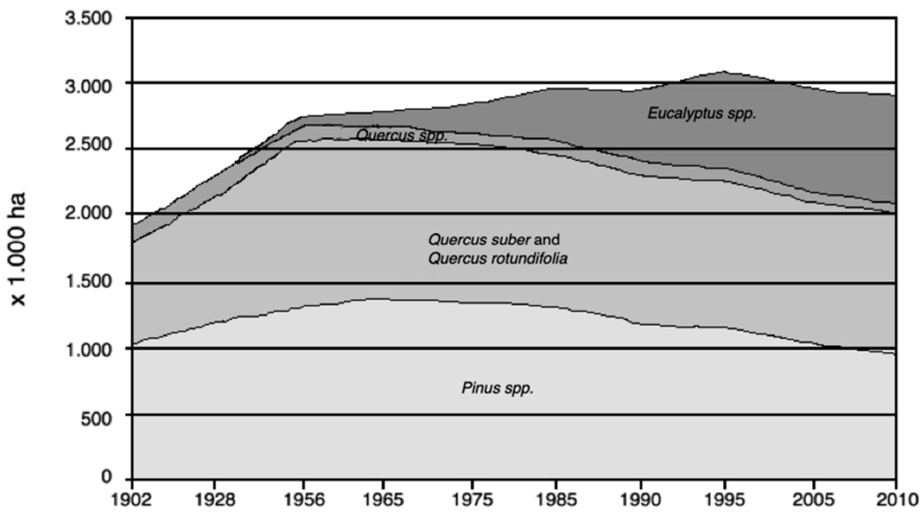

Figure 5. Changes in the area covered by the major tree species in mainland Portugal between 1902 and 2010 (adapted from [27]).

In 1978, the forest area totaled 1,373,891 hectares, representing about 46.5% of the mainland territory. However, some authors thought that the Plan for Forest Settlement had become "an instrument of aggression to the vacant people of the rural areas as being a social disaster" [18]. This situation is still felt today in rural areas, and even in the political environment, where there are frequent references to the way in which the State acts, which has resulted in revolts amongst the population [20,28].

Other authors declared that the launch of the Forest Settlement Plan constituted "forestry management in which productive concern has already overlapped with environmental issues" [18]. This afforestation process may have contributed to accelerating the process of rural exodus and to increasing the vulnerability of forest areas to fires, since half the area was planted with *Pinus pinaster*. The 1960s marked the decline of the complementarity that existed in the use of forests. "Being an integral part of land systems and livelihoods in places and villages" [18], they provided wood for dwellings and agricultural dependencies; resin, pine cones, and wood for heating and cooking; and areas where manure was obtained by the cleaning of shrubs and herbaceous materials [20,29,30].

2.3. Current Forest Development

Currently, according to the data presented in National Forest Inventory 6 (IFN6), about 35% of Portugal's territory is covered with forest. However, according to the same IFN6, this represents a decrease of approximately 150,000 hectares in the period 1995 to 2010, which corresponds to a net loss of 0.3% per year. This decrease is felt especially in the north and central regions, with the conversion of forest use to urban use (around 28,000 hectares) [31].

From the analysis of data provided by the Institute of Nature Conservation and Forests (ICNF), through various documents on its official website, it is possible to verify that the downward trend in forest area in mainland Portugal has continued, with the reduction estimated to have reached 254,000 hectares by 2015 (Figure 6). However, the data are still tentative, as the results of the IFN7 are not yet known, nor is the expected date for their presentation [32].

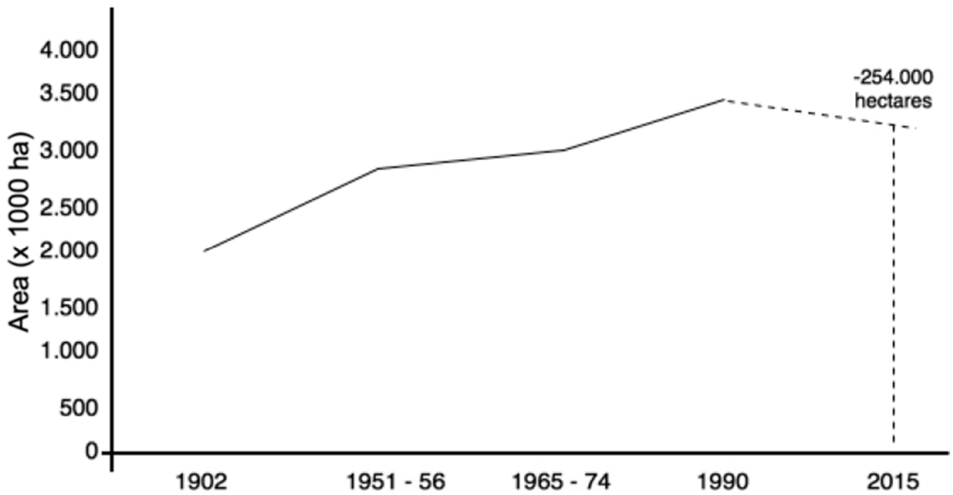

Figure 6. Changes in the forest area of mainland Portugal between 1902 and 2015 (adapted from [27]).

The country's forest structure has changed significantly, but *Pinus pinaster*, *Quercus suber*, and *Eucalyptus globulus* are the three most representative species, representing almost 75% of the forest area. These species are of greatest economic value; they are the species used in the dominant industrial sectors: the pulp industry, agglomerates of wood, biomass pellets, and cork [33].

Eucalyptus globulus became the main species occupying the forest on the continent in terms of area and percentage (812,000 hectares and 26%, respectively), followed by *Quercus suber* (737,000 hectares and 23%, respectively). *Pinus pinaster* (714,000 hectares and 23%, respectively) transitioned from being the main species to the third. The main change in forest area areas between 1995 and 2010 occurred for *Pinus pinaster*, which declined by about 263,000 hectares, and *Eucalyptus globulus*, which increased by about 95,000 hectares [1].

The forest is the basis of a sector of the economy that directly generates about 80,000 jobs [34]. This number has significantly decreased over the last two decades, motivated mainly by the exodus of populations from the interior to the coast, and by the near extinction of activities like resination [35].

These indicators and the increase in production that has occurred suggest an increase in labor productivity in the sector [36].

In the context of forest-based industries, i.e., the industries that obtain their raw materials from the forest and its by-products, the following points are noteworthy:

(1) Sawmills have undergone concentration, with the disappearance of small sawmills. However, it is estimated that the total sales volume will be maintained, comprising about 1.5% of total national exports [37].

(2) The pulp and paper portfolio directly contributes to the creation of around 4,000 jobs, but its main evolution has been an increase in the vertical integration of the sector, with greater production of paper and cardboard, leading to a remarkable increase in the value of the product—a trend that is still increasing. It is the sector with the second highest national value added, corresponding to 5% of national exports [37,38].

(3) The cork industry is an important part of national external trade, accounting for about one-third of total exports of forest products and creating more than 12,000 jobs [39,40].

Cork, perhaps the most beloved of all forest products and which plays a role as a representative icon of the Portuguese forest, has one of the most significant roles in the national industrial environment. The world market is led by a group that, despite its origins in the exploitation of a product of forest origin, has evolved over dozens of years, until it has become an international economic and financial group operating in diverse areas. The AMORIM group goes back to 1870, when António Alves de Amorim founded a manual cork stopper factory at Vila Nova de Gaia. On 11 March 1922, the first company, Amorim & Irmãos, Lda., was officially constituted, with the children of the founder of the first cork stopper as partners. Amorim & Irmãos, Lda. gave rise to the universe of companies that is today CORTICEIRA AMORIM. This second generation gave a new dynamism to the activity of the company and made it a reference for the cork industry nationally and internationally [41].

In 1935, the Amorim family acquired a small warehouse in Abrantes, near the main *Quercus suber* forest area of the country. The acquisition of raw material was made directly to avoid the problem of hoarding by foreign companies. At that time, Portugal, despite being the world's largest producer of cork, only processed about 5% of the raw material, the rest being dominated by foreign entities. The strategy developed by the Amorim family contradicts this trend. It was with this important step towards verticalization of the entire supply chain that the company began to gain importance in forest management, to control as much as possible the production of its raw material, avoiding intermediaries [41].

Even though it does not have its own forestry assets, the scope of its raw material procurement mission is to provide all the needs of the industrial segment. The AMORIM group also promotes long-term projects that ensure the maintenance, preservation, and valorization of cork oak forests and, consequently, the continuous production of quality cork [41].

Currently, the alteration and, especially, the changing of climatic conditions in the regions where the cork oak forests are developed contribute a new set of challenges for the management of these stands. Although the trees are robust and adapted to extreme climates, they require support to continue producing cork, thus justifying the need for the AMORIM group's investment in this area. These projects are developed in partnership with forestry producers, research institutions and local public entities. The AMORIM group's forestry intervention project seeks to create scientific knowledge based on new techniques and processes, and to disseminate and promote new practices to reduce the first cycle of cork extraction, improve the characteristics through genetics and vegetative reproduction of cork oak, and combat pests and disease [41].

THE NAVIGATOR COMPANY, which originated in the 1950s, had its most relevant milestone in 1957 when a team of technicians made the company's Cacia (Aveiro – North Portugal) factory the first in the world to produce pulp from eucalyptus by the kraft process. This was the starting point of a path that would transform a Portuguese company, then called COMPANHIA PORTUGUESA DE

CELULOSE, into one of the world's largest producers of white eucalyptus pulp (BEKP) and uncoated fine paper (UWF) [42].

The growth of the company over more than five decades had several moments. One of those moments occurred in 1975, with the incorporation of PORTUCEL through the integration of several Portuguese factories producing pulp, paper and packaging. At the beginning of the 21st century, an important step towards the consolidation of the company also took place. With the acquisition of PAPÉIS INAPA in 2000 and SOPORCEL in 2001, PORTUCEL consolidated the sector in Portugal. These two steps were decisive and gave rise to THE NAVIGATOR COMPANY [42].

In 2004, SEMAPA acquired a majority stake in THE NAVIGATOR COMPANY. With this new cycle, the company consolidated its leading position in international markets, reinforced in 2006 with the announcement of the construction of a new paper mill in the Setúbal Industrial Complex. In 2009, a second paper mill was inaugurated in the Setúbal Industrial Complex. The construction of this new factory was not only one of the most important milestones in THE NAVIGATOR COMPANY's history, but also a remarkable moment in the country's industrial capacity [42].

With this investment, THE NAVIGATOR COMPANY became the European leader in the production of uncoated printing and writing paper, and one of the largest in the world. The end of the first decade of the 21st century was also a time of great investment in the production of renewable energy and a reduction in the consumption of fossil fuels. One example of this is the significant investments made in 2009 and 2010: two biomass power plants (Cacia and Setúbal), one combined cycle plant (Setúbal) and one steam turbogenerator (Figueira da Foz) [42].

THE NAVIGATOR COMPANY is the largest private forest producer in Portugal, promoting management of 120,000 hectares of forest, with 73% as plantations of Eucalyptus globulus and 27% as diversified plantations. The company has a forest policy and a Code of Forestry Good Practices, which indicate the best practices for the conservation of forest areas, that is, the origin of the business [42].

Another major player in the forestry sector is SONAE INDÚSTRIA, which manufactures products derived from wood, recycled wood, waste from other activities and raw materials from the forest. It was founded in 1959 as an integral part of the SONAE Group and quickly became one of the largest producers of wood-based panels. Located in the north of Portugal, the company underwent a process of expansion through the combination of organic growth and acquisitions, having become one of the leaders in the sector with industrial units in Europe, North America and South Africa, and with a variety of products for the furniture, building and decoration industries that aim to improve people's lives [43].

In May 2016, SONAE INDÚSTRIA entered into a partnership with ARAUCO, a company based in Chile, which is one of the world's largest producers of forest resources. Following this strategic partnership, SONAE INDÚSTRIA holds a 50% stake in SONAE ARAUCO. In addition, SONAE INDÚSTRIA maintains full control of the North American wood-based panel business through TAFISA CANADA, as well as several real estate assets in Europe [43].

3. Historical Evolution of Invasive Species in Portugal

3.1. Exotic and Invasive Species

Throughout the country's history, the forest has experienced advances and retreats, sometimes caused by environmental issues, and sometimes provoked by varying pressure from the population in search of resources to meet their needs. Autochthonous species have not always been capable of providing the necessary answer to the need of the moment, whether sustainable or not.

On several occasions, it was necessary to resort to human intervention to accelerate the process of reforestation, with intensive planting of species considered useful. However, in the very recent past, the paradigm of populations knowing little more than the species they lived in and with which they had always lived in the past, began to change, with the introduction of exotic species from many locations because they were beautiful or could provide a solution to a particular problem.

Thus, begins the legend of the "Pinhal de Leiria" plantation, supposedly ordered to be planted by King Dinis. There is no absolute certainty about who actually ordered the plantation of this pine forest to be created, but there is a strong possibility that it was King Afonso III, the father of King Dinis, or even King Sancho II, his grandfather. Whoever originally planted the pine forest, did it to protect the agricultural fields and the castle from the advancing sands of the coast in the region of Leiria (central Portugal). The pine forest plantation actually increased the forest area since the time of Afonso Henriques, which would have been much smaller and included other species than the pine tree. This may even be the most interesting part of the legend, since it indicates an allochthonous origin for *Pinus pinaster*, because the story says that a group of sailors had returned from the Gulf of Gascony where they had much admired the very tall pine trees that grew in the sand. They saved the seeds and gave them to Queen Isabel, wife of King Dinis, who then went to the sands in Moel, near Leiria, and sowed them to the grown. After a few months, the small trees began to sprout, and the excited Queen showed the King the result of her work. King Dinis, seeing the potential of these trees for his shipbuilding projects, ordered the sailors to bring in more seeds from their next voyages [27,44].

Over the years, many have said, giving even more force to the premonitory tale, that King Dinis foresaw the need to build a large fleet of ships to be used during the period of Portuguese maritime expansion. King Dinis himself established a permanent fleet of boats to counteract the constant harassment of the Portuguese coast by the Saracen pirates, who, from the Moroccan ports and the south of Spain, made consistent incursions on the coast [24].

The spread of *Pinus pinaster* may have begun in force in Portugal and may have existed there in other times but with less range. Since then, *Pinus pinaster* extended its implantation area to the maximum extent reached during the "Estado Novo" period, from 1928 to 1974 at which point one of the largest continuous pine forests in Europe was created, to the point of being almost undeniably considered an autochthonous species. This dispersion encouraged the advance of the fires that seasonally occur throughout the country, especially since the people stopped depending on the pine forest and relied upon other areas, looking for better living conditions and abandoning the traditional activities associated with agro-forestry

In the middle of the 19th century, another species, *Eucalyptus globulus*, was introduced from Australia. The income it generated for forest producers made it an investment that led to a lack of rules guiding where it should and should not be grown, creating continuous forests that, if little managed or not managed at all, create excellent pasture for fires. These are mistakes that time and knowledge are now trying to correct.

Many other species were introduced. One of these is now synonymous of a plague. *Acacia dealbata* Link, which the former National Roads Survey planted profusely, perhaps as an ornamental plant, is a weed that has forced people to invest heavily in their eradication, which is not always successful. Reproducing very easily and quickly, forming densely populated areas that prevent the development of the natural vegetation. This situation is not considered unique, since, in the national territory during the last two centuries, and particularly during recent decades, the number of plant species considered exotic (be they species considered as casual, naturalized or invasive) has grown significantly, reaching approximately 670 species accounting for about 18% of the species found in Portugal [45].

Of all the species of plants classified as exotic that are already found in Portugal, about 15%, several are considered invasive due to their behavior, since they pose a real threat to the natural ecosystems, and even to the land occupied by agricultural crops. The invading behavior depends on certain situations, which are usually the location, soil, and climatic conditions, and response to anomalous situations, such as the occurrence of forest fires. All these exotic species are already well known and well characterized, especially in terms of their provenance, date of introduction, and the reason why the species was introduced [45–47].

Through the promulgation of Decree-Law no. 565/99 on December 21, 1999, and with its updating with the Decree law 92/2019 on July 10, 2019, the national legislation list recognizes the problem caused by these exotic species in the national territory. This law regulates the introduction of exotic species into natural ecosystems, which are non-native species from other latitudes. In this legal document, all the exotic species introduced to Portugal to date are identified, including those considered invasive, and prohibiting the introduction of new species. However, some exceptions have been made, namely for species that provide the potential for afforestation and are of economic interest, among which 21 species of eucalyptus are listed. This law also prohibits the possession, creation, cultivation, and commercialization of species considered to be invasive and that may present a risk to natural ecosystems [45].

With international trade and tourism, it is increasingly easier for species from other countries and continents to reach our territory, some of which are invasive. These reduce biodiversity, affect the ecological balance and economic activities, and can harm public health through the transmission of diseases or parasites. The process for preventing or delaying the spread of an invader is often costly and impossible. Invasive species must be prevented from being introduced. Therefore, the purchase, sale, cultivation, creation, and use as an ornament or pet animal of a species considered invasive or of ecological risk is prohibited [48].

In Portugal, there are several invaders that have been intentionally or inadvertently introduced (e.g., fish or plants disseminated by aquarium water change, accidental escape from captivity, or introductions by importing goods such as exotic wood).

Among the most known and problematic invasive species in Portugal are several species of the genus *Acacia spp*., *Ailanthus altissima* (Mill.) Swingle, and *Pittosporum undulatum* Vent. and *Hakea spp*. quickly form dense forests, reduce the availability of water, and increase the risk of fire [48]. Other species that also behave like invaders are *Arundo donax* L., which does not originate from Portugal [46], and *Cortaderia selloana* (Schult. et Schult. f.) Asch. et Graebn., which is widely used as an ornamental plant.

Some exotic species are attractive from an aesthetic point of view, but it is important to consider the risks they may pose, including that of becoming invasive. Therefore, care must be taken to prevent the proliferation of invasive species. The Portuguese Nature and Forests Conservation Survey ICNF has streamlined various activities for the control of invasive alien species, as well as helped citizens to understand some aspects of this problem related to individual behavior [49].

3.2. *Eucalyptus*

The expansion of eucalyptus in Portugal has produced many lively debates, mainly concerning its negative impacts on the environment, but this has not always been the case. Initially, when it was introduced to the regions of Southern Europe, some of the European colonies in Africa and Asia, and some South American countries in the mid-19th century, it was recognized as having excellent characteristics, quickly gaining interest in these areas [50].

There is no consensus on the date of arrival of eucalyptus in Portugal; the years 1854 and 1859 are suggested [51,52]. Its arrival was related to the chronic shortage of wood that was verified in the country and was common in other regions with a Mediterranean and subtropical climate. A species of rapid growth, its long and slender trunk was a considerable attraction. For the more progressive farmers, eucalyptus provided timber for use on farms and as fuel.

In addition to utilitarian uses, the initial interest, and the values and ideas that prevailed at the time, were conducive to the proliferation of "plant amateurs". Following the "natural explorers" of the previous century, they discovered "the plants of the World" for Europe. Eucalyptus was included in this wave, and although it was discovered on the island of Tasmania in 1792 by Labillardière, it was only 50 years later, after remaining almost ignored in the Botanical Gardens of Europe, that its diffusion occurred [53].

In Portugal, the introduction of eucalyptus and its expansion over many years was not due to any action promoting public forestry, but to individuals, driven by curiosity about the exotic tree in the beautification of parks, gardens, and lands. It was also appreciated for other qualities, including medicinal ones, which were advertised by a qualified group of enthusiasts and publicists, such as

Duarte de Oliveira Júnior, and nursery importers, such as Marques Loureiro, Guilherme Tait, and Rodrigues Batalha, who were merchants from Oporto. Therefore, in this introductory phase of the species, the private owners were the pioneers [53].

In a direct inventory completed by Pimentel in 1884, the presence of eucalyptus in "the most extensive plantations of the country" was well known, showing the predominance of the interest of individuals. Of the 12 properties listed, involving in total some 300,000 trees, the "Pinhal de Leiria" had about 40,000 and "Mata do Valverde" (Alcácer do Sal) had no more than 1,000 trees [53].

In addition to the agricultural and domestic uses of wood, the first clear commercial eucalyptus use was for railway sleepers. Pimentel reported that the first plantations for this purpose were created in 1870 by the Royal Company of the Portuguese Railways from nurseries through the definitive installation in reserved areas of the stations and guard houses, and along the lines [52]. However, there was a long period during which the use of eucalyptus did not increase significantly. Only from the 1940s onward did eucalyptus truly become an obvious and important source of raw material for the production of pulp [50,53].

Questioning of the environmental impacts of eucalyptus, which accompanied the long process of its introduction and expansion (sometimes only as a struggle between enthusiasts and detractors of the species), ran parallel with the lesser role of public options in this evolution. In the last quarter of the 19th century, a Public Forest Administration was created, resulting from the influx of technical and organizational knowledge gathered by a number of notable foresters trained abroad (and some established in Portugal after 1872). This enforced the country's forestation work to combat the centuries-old retreat of forest areas (which produced uneducated, celebrated, and abundant political discussion for a number of decades) [53].

The National Forests Management Survey invested in this objective, culminating in the afforestation plans of the mountains, which began in Manteigas and Gerês (1888–1889). In the work plans of this period, there was no special interest in the use of eucalyptus as a productive species for many years [53].

The dominant action being directed toward the afforestation of the sierras and dunes in the north of the country is largely explained by the lack of interest in the species the last quarter of the century and in the latter part of the 20th century. As a consequence of its better adaptation to ecological conditions, the needs were better satisfied by the pine trees, which due to its characteristics was a pioneer in the occupation of degraded soils [50,53,54].

In the academic world, as well as in the rising research until the 1920s, there was no great interest in the study and dissemination of eucalyptus. A reference index would be the published work on the species. In addition to Pimentel's pioneering and enthusiastic text from 1884, the registration of *Eucalyptus globulus*, still in exclusive botanical description, is only found in the Course of Forestry by António Xavier Pereira Coutinho (1886) with five other species of eucalyptus. In the analysis of the final reports of a forestry course from 1872 to 1920, only a dissertation on "exotic forest essences to be cultivated in Portugal" provides the botanical-cultural description of the species [53,55].

Until the 1940s, the number of publications was scarce. In a widely used forestry manual, the Notions of Forestry by Horacio Eliseu (1926 and 1942), which listed species recommended for the use in the afforestation of the continent with dendrological and cultural information, there is no record of Eucalyptus globulus among the three dozen species described [53,55].

The 1920s and 1930s created situations that led to changes in context to influence the great expansion of eucalyptus. One case is reflected in the first steps taken at this time by the Public Administration in the organization of forest research with the creation of two institutions for experimentation [23,53,55]. Here, work began on the technology of forest products that led to the installation of a Cellulose Laboratory in the early 1940s, in which Portugal's different species were systematically studied from the perspective of their industrialization. In 1925, CAIMA, a company established in Portugal in 1888, used other raw materials, particularly the pine tree, to commercialize the pulp obtained from eucalyptus while developing its own plantations. The State also continued afforestation, with preference for the planting of hills. The Plan of Forest Settlement of 1938 was executed, but there was no change in its characteristics and their products [53,55].

In the 1940s, however, there was an intensification in the discussion about and the launching of an industrialization policy in the country. This occurred via a permanent polemic between industrialists and ruralists, and the Industrial Development and Reorganization project was approved. Law no. 2005, dated 14 March 1945, provided an important intervention and state support in the creation of industries. In relation to the pulp industry, the order of 12 March issued a license "for the installation of a pulp mill, mechanical pulp, newsprint, and other papers" to COMPANHIA PORTUGUESA OF CELULOSE (Cacia), which started operation in the early 1950s, after the combination of interests between industrialists and Portuguese bankers, with intermediation of the State, and was the first Portuguese project under the support of the famous Marshall Plan [53,54].

The raw material used from the beginning was the pine tree; only later did the use of eucalyptus become important. Eucalyptus was, therefore, a strong option for industrial public policy, which would have a marked effect on forestry, in particular policy of forestry and the agriculture sector, which was always resistant to such developments. In 1959, when the Ministry of Economy was defined as the main line of political action for agricultural industrialization and specifically mentioned the case of eucalyptus pulp production, cooperation became necessary between the three sectors of economic governance: industry, trade, and agriculture [53].

The reluctance to expand eucalyptus production was based on ecological grounds justifying its negative effects, although at that time hardly elucidated. Some misunderstandings were due to the spread of plantations to locations that were not indicated and were much more grounded in the tradition of defense of the "essentially agricultural country" that originated in the 19th century. Therefore, the fear of loss of areas was judged to be more interesting for agriculture at the time. This explains not only the resistance to the expansion of eucalyptus, but more generally to afforestation itself, providing a reason for the lack of success of some public initiatives. Law No. 2069 of 1954 created conditions for afforestation of private property, which was followed by the realization of plans for afforestation of some hydrographic basins of the south of the country. Since the introduction of the law, very little materialized. A proper body was created to achieve this objective, the Forest Development Fund (1965). In the short-term, its action was mainly limited due to financing problems in the sector of public administration responsible for the agriculture sector [53].

As far as eucalyptus is concerned, the roots of innovation in terms of silviculture techniques, such as soil preparation and plant production, were conducted for the application of Law 2069. The activities were mainly conducted by Ernesto Goes and the field teams set up at the time, which allowed the expansion of the geographical areas of eucalyptus but also increasing productivity [53].

From this time on, under the influence of the owners' interest and the pressure of the expanding industry, which was devoid of raw materials, eucalyptus was extended to include the area of exploitation of the industrial companies themselves with support from several origins, ranging from the World Bank to European funds. The plantation areas have expanded from 100,000 hectares by more than six times to date.

The area of eucalyptus cultivation, therefore, expanded slowly until the 1950s (Figure 7). From that time, the area grew continuously until the 1990s, registering a slight decrease in the last National Forest Inventory (2010). The inventory refers to the existence of 295,500 ha of young stands, and a considerable part of this area corresponds to eucalyptus plantations. Excluding the area of these young stands, the eucalyptus area (647,000 ha) represents about 19% of the country's forest area (3,412,300 ha) [53,56].

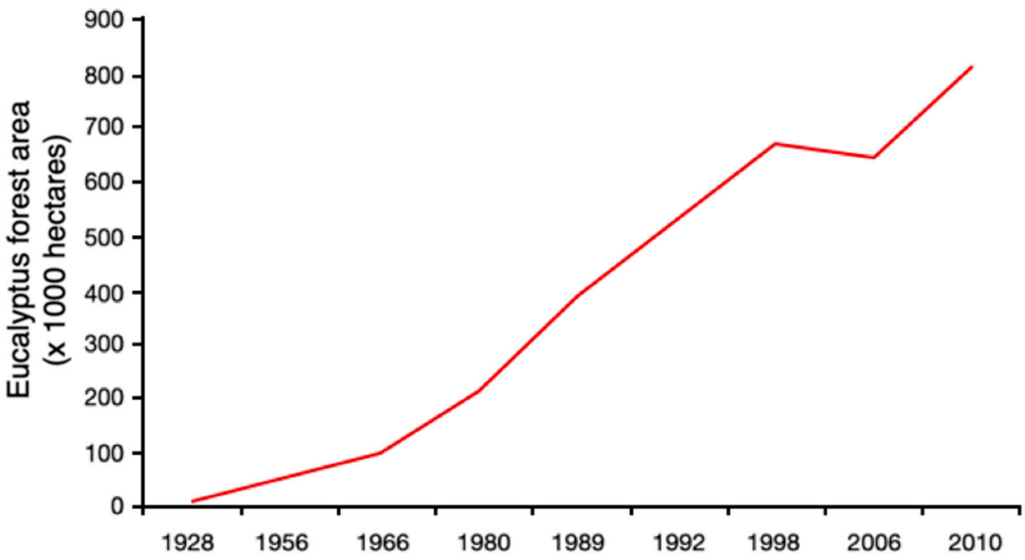

Figure 7. Changes in the area covered by eucalyptus in mainland Portugal (adapted from [57]).

In the second half of the 20th century, the expansion was roughly parallel to the growth of the pulp industry. At present, all the eucalyptus wood used in the national industry is sourced from national forest, and 90% and 77% of pulp and paper sales, respectively, are exported [56].

The intensification of the crop, allowing for production in periods incomparably shorter than the general lifespan of the forest species, was economically attractive, especially in the context of the emerging rural depopulation in the middle of the 20th century. As stated above, environmental concerns, although in embryonic and non-global forms, are no longer a problem today. Earlier, for example, farmers faced decreases in agricultural production in areas adjacent to plantations or windbreaks of eucalyptus. Although it is easy to explain and cannot be generalized, this border effect resulting from the intense consumption of water by the border tree lines has made eucalyptus a subject of controversy [53].

Some legislative interventions were introduced, notably when Law No. 1951 of 9 March, 1937 was published, which prohibited the planting of eucalyptus trees less than 20 m away from cultivated land and less than 40 m from water springs. The environmental debate was stronger in the 1970s and 1980s as a result of the visibility of the expansion of plantations and the opportunity to politicize environmental issues [53].

The controversy was not only confined to Portugal because it covered most of the countries where eucalyptus was used as an intensive crop for the production of wood, paper pulp, or fuel—India, Ethiopia, Brazil, and South Africa—but the arguments were incipient and combined different aspects. For example, the socioeconomic issues that related to the conversion of agricultural and agroforestry lands into eucalyptus plantations were mixed with ecological effects, which were often imaginary. Legislation to limit the expansion of the eucalyptus was introduced in Portugal, highlighted by Decree-Law no. 175/88 of 17 May, 1988, which aimed to prevent the proliferation of large continuous areas of eucalyptus, as well as to convert cork oak and holm oak plantations into eucalyptus plantations [53].

The expansion of eucalyptus cultivation in Portugal occurred at a time when, in the increasingly urbanized Portuguese society, attitudes and philosophies of environmental defense and conservation of biodiversity were growing. Within this context, in which the values of agrarian productivism were confronted by imaginary environmental protection, the modern environmental challenge to the cultivation of this species developed [53,58].

The perception of the forest and the paradigms of its management have shifted, where environmental benefits are increasingly valued in comparison with commodities such as wood. The image has been shifting from the "industrial" forest to the "post-industrial" or "post-productivist" forest [59]. The environmental benefits, however, tend to revert in favor of the general population, and it is difficult for forest owners to convert them into economic value [53].

3.3. Acacias

The thinker, essayist, and poet Jaime Magalhães Lima, who was born and lived in Aveiro (Portugal), dedicated some of his work to the study of eucalyptus and acacia trees, and in his 1920 work, "Eucalyptos e Acacias - Twenty Years of Experiences", he classified acacias as being "the miraculous baptism by which sterility converts to culture" [60]. At the time, where knowledge about evolution, dispersion, and growth rates was yet to be established, many people, more or less literate, admired the rapid growth of these plants for the economic benefits they provided, the quantity and quality wood that they supplied, the beauty of the flowers, and the gardens that could be produced in a short time. In this work, the author discusses the occurrence of eucalyptus and acacia trees in Portugal at the time, mainly as ornamental species, and that were brought by travelers from other places. The work was published at a time when people were more likely to experience astonishment at the unknown, without much technical and scientific knowledge, than have concern for the environment.

Although the dangers associated with the proliferation of the species in this group are now known, it is necessary to recognize that these species are a prodigy of nature given their resilience and adaptability, posing a risk of rapidly becoming weeds to the detriment of autochthonous species.

The acacias constitute a vast group of species, distributed mainly in the Southern Hemisphere. Observation of the habitats of origin of these species showed that when they are in their original environment, they are associated with many other species, contributing to the profusion of biodiversity, adapting to different environmental conditions, coexisting with other plant species, and providing shelter and food for various animal species. These original habitats are found mainly in Australia, which accounts for 75% of the tree species and forest shrubs, together with the eucalyptus [61].

Among these many species, there is one that, mainly due to its spectacular flowers (Figure 8), quickly aroused attention as an ornamental plant. *Acacia dealbata* has yellow-bright globular inflorescences in bloom with beautiful yellow curls of flowers. Unfortunately, the "miraculous" acacias are no longer restricted to the southern continents from which they originated, becoming a pest that is threatening many ecosystems far away from Australia, including those of Portugal [61].

Figure 8. *Acacia dealbata* flowers.

The acacias form a group of about 1,380 species, 1,000 of which are native to Australia, with the remainder native to the other continents of the Southern Hemisphere, except for some species that originated in North America [62]. Differences exist in the classification of the family to which acacias belong. Some authors place them in the large legume family (Leguminosae), whereas some authors claim that they belong to an independent family, the Mimosaceae [63,64]. Like other leguminous plants, acacia seeds are grown in small pods, which open at the time of seed release [62].

As an essentially Australian species, acacias are well adapted to hot and dry climates, with regular occurrence of forest fires. Many acacias may be called pyrophytes, species for which fire acts as a stimulus of growth and dispersal [61]. Thus, in areas where the climate is hot and dry, as in Southern Europe, acacias are well prepared to compete with native species for resources such as space, water, and nutrients, as well as for regular fires to facilitate dispersal [65].

Humans, since ever, introduced intentionally or unintentionally non-native species to other regions, and species that were previously restricted to a given area can now be easily be transported to the other side of the world. These non-native plants, which are designated exotic, may not cause major problems. In many cases, the new habitat does not have the ideal conditions the species had in its original habitat. Sometimes, however, the exotic species exhibits biological characteristics, such as rapid growth, formation of more seeds, and alteration of the characteristics of the medium, that make it a formidable competitor in a place where it is not native. In these cases, it becomes an invasive species, and this phenomenon is called biological invasion [66]. In Portugal and most of Southern Europe, the most problematic species are *Acacia melanoxylon* R. Br. in W. T. Aiton, *Acacia longifolia* (Andrews) Willd., and *Acacia dealbata*; the latter generally has the greatest impact because it forms the largest clusters and is the most-dispersed species [67]. Like most other acacias, this species is native to Australia, but it does not originate from the warm inland deserts. It can be found in South Australia and Tasmania in areas of more temperate and humid climates, with low precipitation and mild temperatures [68]. Its habitat is open eucalypt forests, but it easily adapts to other conditions. Although it prefers mild climates, it is still a species well adapted to environmental conditions where fires are frequent [69].

At the end of the 18th century and beginning of the 19th century, specimens of this plant began to be brought to Europe, initially by British and French navigators, who first disseminated them through colonies in South Africa or Madagascar, before arriving in Europe [70]. The main reason for their dispersion and acceptance by Europeans was their beautiful flowers, although the wood was appreciated as well as their ability to set slopes [57].

The first records of the occurrence of *Acacia dealbata* in Portugal indicate its use as an ornamental plant in the second half of the 19th century. This was indicated by an article written in 1871 in the Journal of Practical Horticulture on a planting of silver wattle in Oporto, which offered "a coupon that gave subscribers the right to receive a free package of *Acacia dealbata* seeds" [71].

For a long time, mimosa and other acacias continued to be seen as species of exceptional economic or botanical value. Despite observations of its invasive nature, it was only in 1937 that the first legislation was introduced to control the planting of *Acacia dealbata*, although this only controlled minimum distances for sensitive terrain such as pastures, agricultural plantations, or slopes [57,72]. It was only in the 1970s and 1980s that this problem was seriously considered, but at this time the main centers of expansion were related not to plantations but to forest fires that allowed this and other acacias to rapidly colonize land previously occupied by native species [73].

Once colonized by acacias, native species struggle to develop in these areas because, in addition to growing quickly, they create an extensive seed bank in the soil that allows rapid re-colonization in case of disturbances such as fires or removal of vegetation. Their leaves have toxic compounds that inhibit the growth of other plants when they accumulate in the soil (a phenomenon called allelopathy [74]), mainly altering the chemical composition of the soil [75,76].

As already mentioned, acacias belong to the legume family, which are specialists in forming symbiotic relationships with nitrogen-fixing bacteria at their roots [65]. Although the soil is richer in this essential nutrient, the invasive characteristic of the acacia quickly causes any soil full of these plants to have a chemical composition different from the original, which specifically benefits acacias compared to native plants [77].

Some studies have been conducted in Spain and Portugal where soils with *Acacia dealbata* and *Quercus robur* L. demonstrate the differences they have suffered [78–80]. These studies verified that mimosa-invaded soils have lower biodiversity, more propensity for other exotic species, less ferns and mosses, are richer in nitrogen and have a more acidic pH [81]. These changes in soils are reflected in the remaining biodiversity, the water cycle, and all other processes and functions in an ecosystem [82].

Cutting acacia trees combined with the use of herbicides, or peeling to cause dehydration, may be methods of control (Figures 9 and 10). However, given the seed production capacity of these species, even if all plants were removed at any given time, there would still be enough seeds for them to continue to burst for many years [83].

Figure 9. Application of herbicide, in this case glyphosate, after cutting an *Acacia dealbata* tree.

Figure 10. Peeling of *Acacia dealbata*. The peeling technique should cause all the bark to be peeled from approximately 1.30m to the root.

The best method, apart from the removal of these plants whenever possible, is to prevent their invasion in places still free of the influence of these weeds, conserving the forests and other native habitats. The more natural and stable a habitat, the less chance of invasion occurring, as invasive plants have more difficulty in finding resources not yet used by native species [84].

Another hypothesis that has been studied is the introduction of natural predators of acacias into their habitat, as has already been used on a large scale in South Africa with good results [85]. In Portugal, the species of wasp *Trichilogaster acaciaelongifoliae* (Frogatt) has been tested on *Acacia longifolia* with promising results, but care must be taken in the introduction of this wasp to ensure that this species will not begin to attack autochthonous plants, thereby creating another invasive species [86].

4. Conclusions

Forest is a complex system that is constantly evolving and adapting to new environmental conditions. Forests are also being subjected to increasing pressure from human activities that exploit them. Such exploitation confers several benefits that are rarely, if ever, undertaken from a sustainable use perspective and that prevent evolution and adaptation from occurring over a period of time consistent with the recovery capacities of the natural environment.

Concerns have been consistently expressed throughout history about the ability of forests to recover, not because of widespread environmental awareness, but rather because humankind has always been aware of the need for forest resources for subsistence, implementing permanent reforestation plans. It is these plans that, given new environmental and climatic constraints, must consider all the variables involved in the evolutionary and adventive processes. These processes should not ignore, for example, the presence of invasive forest species and creation of control mechanisms for their dispersion. It will be difficult to irradiate these invasive species, except in very restricted and concrete areas, given the available resources.

Portugal has experienced periods where its forests have evolved, regressed, progressed, and transformed, with its soil being used for other purposes. These changes were sometimes driven by natural changes, while at other times they occurred by human hand. The forest, like any living system, continues on this evolutionary and adaptive course, always affirming, at any time in history, to be fundamental to life, and to be a source of wealth, providing some of the most beautiful scenery in the country.

It is from this perspective that the Portuguese forest reaches the present day, with a set of important challenges that mark its development and evolution in the coming times. At this time, contrary to what has happened in the past, when alterations occur alternately with a more significant weight of the natural changes of the environment, or through anthropic intervention, the forest has to simultaneously evolve and adapt due to natural and human influences. Even natural influences may also be enhanced by human action.

The phenomenon of climate change, the introduction of species into new habitats, the intensive deforestation for industrial and commercial purposes, or the change in land use for other purposes, namely agricultural production, have only occurred at their historical rates due to the influence and intervention of humankind.

Today's rapid changes, many of which are similar to those from the past, make knowledge of these historical events important because they allow solutions to be found by comparing facts. Thus, it is understood that it is in the course of historical events that solutions can be found, often by antagonism, but essentially by avoiding the mistakes of the past.

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CHAPTER 2 – Framework

Chapter Index

forests

MDPI

Review

Socioeconomic Aspects of the Forests in Portugal: Recent Evolution and Perspectives of Sustainability of the Resource

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Abstract: Portuguese forests have always played an essential role in the socioeconomic development of national rural areas, but also in several forest-based industrial sectors, such as the cork, pulp and paper, and wood panels industries. In addition to these dominant sectors, there are also several other uses for forest timber, such as being the major raw materials to the production of furniture or devoted to the growing biomass pellets production industry. This review article presents the evolution of the forest industrial sector throughout the recent past, and its impact on the development of the rural environment, from a socioeconomic perspective, namely concerning the jobs and value-added creation, as well as the importance of the forest in national industrial development. It shows the importance of sustainable forest management for the development of the rural environment, as an essential sector for the creation of wealth and for the establishment of populations in the interior regions of the country.

Keywords: forest resource; forests management; sustainable development; rural environment

1. Introduction

Throughout the path that humans traced in their evolution until reaching the current civilizational state, especially in the countries that constitute the so-called First World, societies always used the resources that the natural environment made available to the communities [1–3]. In a first phase, these resources were simply collected and used in a primitive and direct way, without any kind of processing, and the communities lived or tried to live as close as possible to the resources needed for their subsistence, moving in search of new sources as soon as a particular place exhausted the possibility of satisfying the demand, essentially, for food [4–6].

Forests have always been privileged spaces to meet the basic needs of humans, being the place where primitive populations could find provisions that guaranteed their survival, but also refuge and other products such as wood, bark, and leaves for the construction of shelters, and later fuel, after the discovery of fire [7–9].

As time passed by, humans learned how to use forest resources in their advantage, even destroying the area occupied by the forest for other purposes, namely agriculture. However, this connection with the forest space remained until the present day, and it is inseparable from the need that the current societies maintain for forest products [10,11].

This long journey of thousands of years that humans covered and the established connection with forests have radically and definitively transformed the development of this natural space, and this is probably the reason there is a predominance of certain species at the expense of others. That is, and can be said that, with some exceptions, most of the forests that exist today had their development in some way conditioned by the action of humans [12,13].

Portugal, as a country that saw its territory occupied by humans at an early stage, is one of the best examples to analyze this evolution of forests over time, both in terms of human occupation and the impacts caused by the use of the natural space, but also in a more ecological perspective of the environment, where it is clearly possible to verify the way in which forest species were selected for having more or less interest to satisfy human communities' needs [14].

One of the best examples of this evolution and conditioning of the forest space by human activity is the "Montado Alentejano", the traditional cork oak forest in Alentejo, which results from the adaptation of the Mediterranean natural forest to the needs of the populations that inhabited this territory of southern Portugal, the "agro-silvo-pastoril" system, since it covers agricultural, forestry and livestock use, and it is this overlapping of uses that made it sustainable for thousands of years, and clearly one of the most prosperous [15–19].

This model, which has been distributed a little throughout the country, always adapted to the characteristics of each region, was the model that defined the rural world throughout the times and that even reached the present days, proving the diversity that it is possible to identify among Portuguese regions. However, as the resident population grew, so did the need for more resources, leading to the overexploitation of forest resources, causing a significant reduction in the area occupied by forests in the national territory [20].

It was this slow but consistent reduction over an extended period of time which forced the Portuguese government at the beginning of the twentieth century, during the so-called "Estado Novo" regime (literally, New State), which was a form of authoritarian, autocratic, and corporatist state political regime that controlled Portugal for 41 years without interruption, from the approval of the Constitution in 1933 until its overthrow by the Revolution of April 25th 1974, to take measures to reforest the country, initiating the process that led definitively to the creation of a forest-based industrial sector, with focus for the great reforestation projects that begun in the 1960s but that had an impact mainly in the years following the revolution that established democracy in Portugal [21,22].

This review article intends to make a historical approach of the evolution of the forests in Portugal through recent times, highlighting how forests' development and management influenced rural environment in the period after the revolution of April 25th, 1974 until today, giving at the same time a perspective of sustainable development of the resource.

2. The Evolution of Portuguese Forests

As mentioned previously, Portuguese forests underwent a set of changes of anthropic nature that conditioned its evolution throughout historical times and served as a basis for many important landmarks in the History of Portugal, such as the Portuguese discoveries and the maritime expansion. In this period, forests served mainly as a source of raw materials for shipbuilding, in addition to all the other more common and frequent functions [3,23,24].

Due to this excessive use, and without organized policies to replace the resources used, Portuguese forests reached the beginning of the 20th century with an area of approximately 640,000 hectares, most likely corresponding to the smallest area ever. It is from this starting point that the recovery process begins, mainly after the establishment of the republican regime in 1910, with specific policies for the reforestation of the country [23,25].

However, it was necessary to reach the "Estado Novo" period, in 1933, to start a real forest recovering policy that attained great development from the end of the decade of 1950 and during the decade of 1960, with a large forest expansion at national level, with the plantation of hundreds of thousands of hectares of maritime pine (*Pinus pinaster* Aiton) in the inland mountains and coastal areas of Central and Northern Portugal, defining the beginning of landscape evolution to what it is known today. This new forestry order, based on the maritime pine culture, allowed the development of a set of associated industries that contributed greatly to the creation of jobs in rural areas, but also to the establishment of a new industrial sector in which Portugal was a world leader for decades, the resin and rosin derivatives sector [26,27].

It was this maritime pine priority as forest culture, decades later, in the post-revolution period, that became the basis for the development of other types of industries, namely the production of wood panels and biomass pellets. However, it was another type of crop that played a determining role in the evolution of the forest organization and which also began in this period. This was the beginning of the large-scale plantation of eucalyptus (mainly the species *Eucalyptus globulus* Labill.), destined to feed the pulp and paper industry, in which Portugal also become one of the world leaders, namely in the production of bleached pulp [28–30].

On the other hand, in Southern Portugal, where the dominant species is cork oak (*Quercus suber* L.), the occupation rate of the soil has remained more or less stabilized, most probably due to the millenarian use of the soil with the tripartite agriculture–forestry–livestock components, which have always guaranteed the sustainability of the system. The silvicultural component played an increasingly important role, mainly due to the high value attributed to cork, since it started to have other applications than the traditional production of wine stoppers. Thus, there was an increasing interest in maintaining the cork oak forests, thus ensuring continuity of the remaining components of the system, since they only added value and did not interfere with cork oak productivity [19,31].

In recent years, forest structure has changed significantly, but it can be seen that maritime pine (*Pinus pinaster*), cork oak (*Quercus suber*), and eucalyptus (*Eucalyptus globulus*) are the most representative species, occupying around 75% of the forest area, and those with greater economic interest as well. In other words, those are the species predominantly used for industrial applications, such as the pulp and paper, wood panels, biomass pellets, and cork industries [32]. Eucalyptus became the main forest culture in mainland Portugal in occupied area and percentage (812 thousand hectares, 26%), followed by cork oak in the second place (737 thousand hectares, 23%), and maritime pine (714 thousand hectares, 23%) went from the first to the third species. The main change in areas of forest species between 1995 and 2010 occurred with pine tree, which saw a decrease of about 263 thousand hectares, and in the area of eucalyptus, increasing by about 95 thousand hectares [33]. However, in this context, the pine tree area in Portugal continues to be particularly important and presents a worrying trend of reduction and difficulties in supplying the established value chain for its products and derivatives, and it is necessary to develop specific policies for its recovery. In order to exploit this immense potential, several conditions must be met, namely:

- Consistent policies, tailored to their targets and operationalized in long-term stable programs that solve the problems that threaten the regions of North and Center Portugal, ensuring the maintenance and sustainability of the forest and its resources;
- A disruptive approach to the development of new forest/territorial management models that reduce risks and enable investment and forest profitability in areas of smallholdings;
- A clear strategy to promote the circular bioeconomy and sustainability in rural areas.

3. Socioeconomic Aspects of the Forest Industry

This new paradigm of forest evolution, as a source of resources in an intensive perspective of supply of a set of industries that have been developed due to the abundance of raw materials, led to a forest management model based on the plantation of a restrict number of species, which occupy significant areas of the country [34,35].

In fact, according to the most up-to-date data available on land use in Portugal, which refer to 2015, the forest occupies about 39% of the total area, and of this area, 72% is occupied just by 3 species, namely maritime pine with 23%, eucalyptus with 26%, and cork oak with 23%. That is, 28% remains for all other forest species that can be found in Portugal [36].

The combination of this forest organization contributed to the growth and development of several industrial activities mentioned previously, and which occurred in the years immediately after the revolution of 1974. Forest-based industrial sectors actually represent 2% of the national Gross Domestic Product (GDP), contribute with 2.6 billion euro to the national trade balance, and as a work base for seven thousand companies, responsible for 115 thousand direct jobs. It was precisely in this post-revolutionary period that Portugal reached the leadership of the pine resin industry and in the production of pine rosin derivatives. It was a prosperous industry which saw an increasing use of these compounds as raw material for the production of a large number of products, and which had its peak exponent during the 80s of the twentieth century. During this period, resin extraction functioned as a seasonal complement to rural workers, who intercalated agricultural exploitation with resin collection, being the forestry management model mainly directed towards this end [37].

With the admission of Portugal into the European Community, a new period of economic growth and development emerged, which will definitively change the current situation. With the arrival of European community funds for the development of infrastructures, civil construction became the country's main economic activity, creating hundreds of thousands of new jobs, which were filled mainly by former agricultural and forestry workers, leaving both sectors practically abandoned. This was the beginning of the end of the resin sector in Portugal, which only survives today due to the importation of raw materials from new producing countries like Brazil or China [38].

This abandoned land was the ideal stage for the emergence of a "solution" that promised income with little or no management at all, and a rapid return when compared to other forest crops. It was in this way that in the late 1980s and throughout the 1990s, the great expansion of eucalyptus occurred in Portugal. This species had a number of unbeatable advantages, namely a faster growth when compared to traditional forest species, and a growing demand from the pulp and paper industry, which ensured its flow and created a value chain. However, perhaps the most important argument was that the pulp and paper companies were willing to lease the land and support the costs of investing in the plantation of eucalyptus, allowing land owners to continue to have some kind of income from the forest, without the need of a nonexistent labor force that shifted to coastal regions to work in the construction industry [38,39].

According to data presented in IFN6—National Forest Inventory 6, Portugal has an area of about 35% of its territory covered by forests. However, according to the same IFN6, this represents a decrease of approximately 150 thousand hectares in the period 1995 to 2010, corresponding to a net loss of 0.3% per year. This decrease is felt especially in the North and Central regions, with the conversion of forest soil use to urban use (around 28 thousand hectares) [33]. Presently, the forest area corresponding to cork oak has shown a slight growth, as the data presented in the Portuguese Soil Use and Occupancy Mapping, COS 2015, indicate, and corresponds to an increasing need of cork, which has become the fundamental raw material for several industrial applications. This collection of cork has allowed rural populations to adapt to seasonality and specific rotation, combining this with other economic activities in a sustainable way [40]. From the analysis of data provided by the Institute of Nature Conservation and Forests (ICNF), through several documents available on its website—www.icnf.pf—it is possible to verify that forest area in mainland Portugal continues in a downward trend, with a reduction estimated in 254,000 hectares in 2015, although these data are still provisional, as the results of the IFN7 are not known yet, nor the expected date for their presentation. This reduction in forest area goes against the trend of the previous period, where it was possible to see a continuous growth (Figure 1).

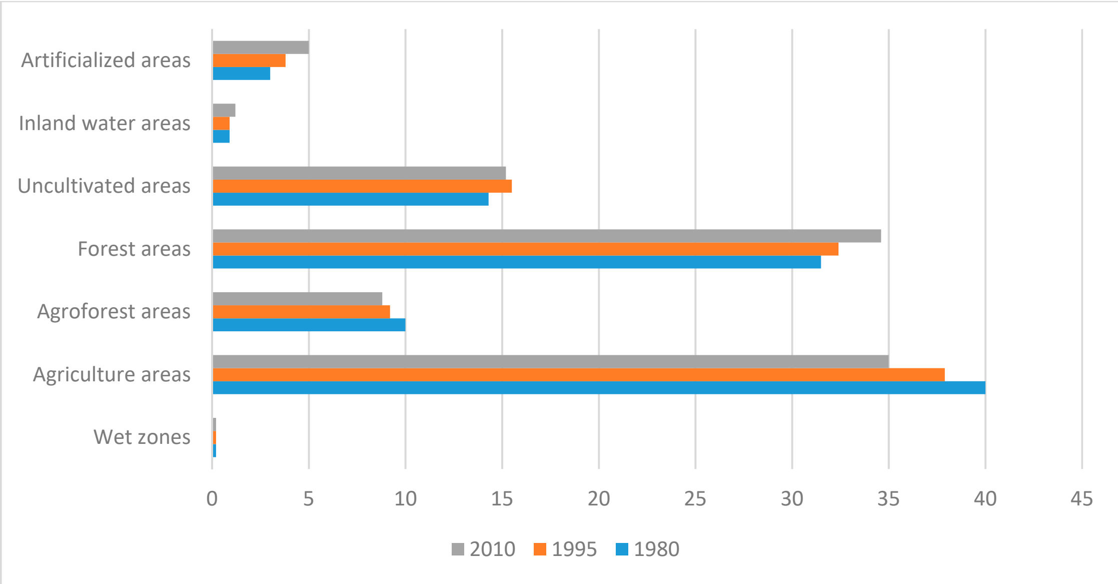

Figure 1. Areas of occupation for different land uses in Portugal (adapted from Reference [41]).

In this same perspective, it can be seen that in comparison with its European counterparts, Portugal has had a decrease in the total forest area, completely against a counter cycle, since, as can be seen in the analysis of EUROSTAT data [42], the trend in the main European countries is the growth of forest areas. In the same referred document, especially when comparing the variations which occurred between 1990 and 2015, it is verified that the general trend is to increase the forest area, except for Portugal, Estonia, North Macedonia, and Sweden. In this circumstance, Portugal presents the greatest negative variation, most probably due to the action of rural fires that seasonally affect the national territory and that periodically occur with a frighteningly large scale [43]. Sweden, as one of the precursors of the use of biomass for energy, showed a decrease in its forest area, which, however, had already begun to be the subject of a recovery and intensive reforestation project, in order to maintain its sustainability. This plan already led to the stabilization of the forest area, with a similar trend in other countries [44]. Estonia, for similar reasons to those identified for Sweden, also saw its forest area reduced, most likely caused by the country's entrance into the international market of biomass pellets as one of the leading producers [45]. However, as can be seen, this decrease has already stabilized, and it is expected that the trend will be reversed (Figure 2).

Regarding forest ownership in Portugal, ICNF describes in the "Forest Profile" [46] that "Portugal occupies a sui generis place regarding forest property regime, with only about 3% of forest lands being owned by public entities (State and other public entities), being the remainder held by local communities (the so-called "baldios", about 6%) and private owners (92%, 4% of which are managed by industrial companies)" (Figure 3).

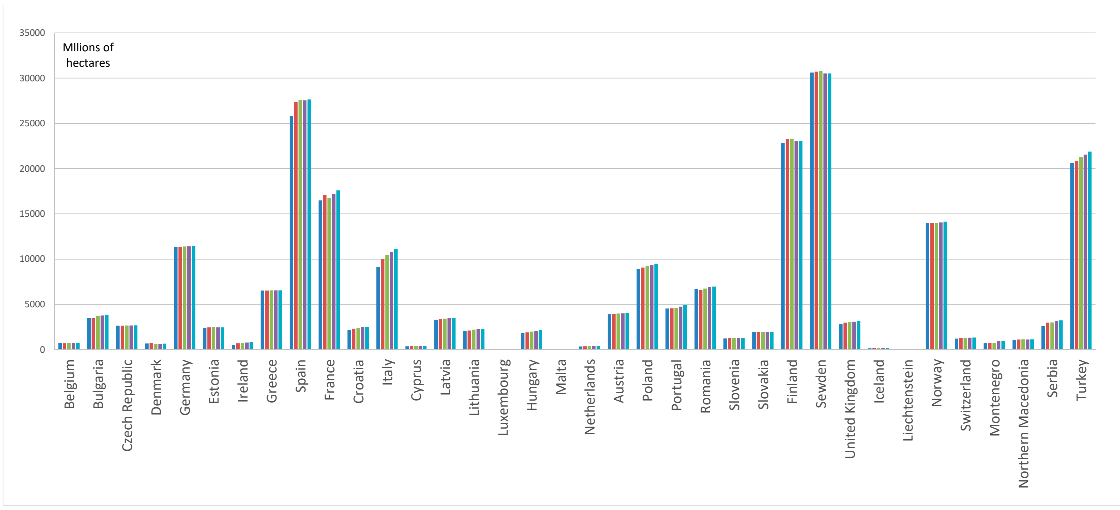

Figure 2. Evolution of forest area in European countries for the periods 1990, 2000, 2005, 2010, and 2015 (adapted from [42]).

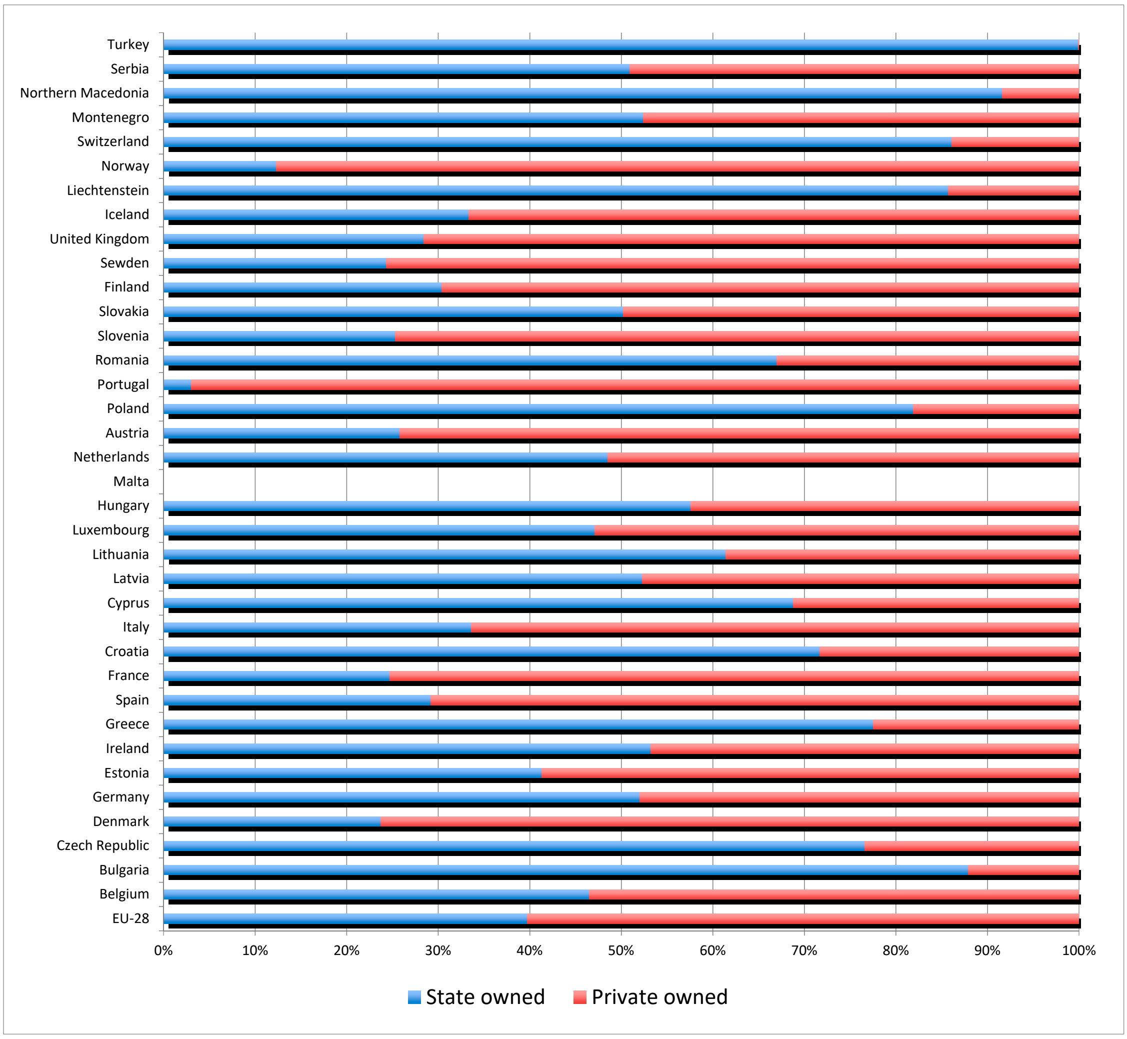

Figure 3. Distribution (%) of ownership of forest property in European countries (adapted from [42]).

The same "Forest Profile" states that "there are 11.7 million rustic buildings registered in the matrix (therefore with agricultural or forest use), and only 46% of forest areas have a land register. It is estimated that more than 20% of the territory has no or unknown owner." This situation contrasts with countries such as Spain or Greece where, respectively, public forests reach 30% and 75% of the total forest area. The average size of forest property in Portugal, which is around 2 to 4 hectares, is small, which also justifies the great fragmentation of forest property [47]. According to the Global Forest Resource Assessment 2010, Portugal is among the countries in Europe with the highest percentage of private forest area, where private property corresponds to 3.4 million hectares of forest areas, 98.4% of the total, of which 5.2% belong to industrial companies [47].

4. Forest Induced Development

The dynamics of territorial evolution and transformation can be considered one of the most important components in the evaluation of terrestrial environmental systems, since they reflect the impact of human activities on the global environment [48]. Thus, in the evaluation of territorial dynamics two different perspectives of analysis can be used, one being the identification of the dynamics or, on the other hand, the identification of the driving forces that cause these dynamics of transformation and/or evolution [49]. Recent literature has identified three essential elements in the transformation process of land occupation: Driving forces, actors, and land use [50,51]. While the last two are specific to each territory, the analysis of driving forces is more diffuse and can be divided into five areas, specifically, politics, economics, culture, technology, and natural/spatial. Due to the specific diversity of each area and the objectives of each assessment, different approaches can be used to study the transformations of land use and the evolution that these can present, namely in the concrete situation of the forest occupation, its development, determination of trends, the sustainability of the resource and the expected impact of the different socioeconomic descriptors [52,53]. These approaches can be spatial vs. nonspatial, dynamic vs. static, descriptive vs. prescriptive, deductive vs. inductive, global vs. regional. However, other approaches can be chosen, as demonstrated by several papers published by many authors, adopting a great variety of methodologies [54].

As was verified in the previous sections and giving focus to the analysis of the driving forces that caused it, the recent evolution of the Portuguese forest can be divided in 3 distinct periods. The first corresponds to a period of forest decline, in which the forest regenerates almost exclusively in a natural way, ending approximately after the implantation of the republican regime in 1910, and the beginning of the period known as the "Estado Novo" in 1933. The second period corresponds to the duration of the "Estado Novo", where reforestation policies were planned and where the forest came to be seen as a resource that has to be managed, mainly with the development and incentive to plant extensive areas of maritime pine, as a way to minimize the recurring shortage of construction timber and firewood that the country was experiencing. The third period corresponds to the time interval that began with the revolution of 25th April 1974 until today, where forests were definitively seen as a source of resources for several industries, among which the pulp and paper, wood panels, and cork industries, but also for other emerging industries such as the production of biomass pellets for energy [3,55,56].

The rural world evolved within these periods, following the different developments that occurred in the forest, which somehow became mutually conditioned but that allowed rural populations to subsist in a sustainable way, mainly due to the complementarity of activities, which were interspersed and created a sequence of interconnected tasks [57].

The emergence of new activities, such as those that began with the construction boom after Portugal's admission to the European Union, and which encouraged the greater migration of people to coastal regions, which took place in the post-revolutionary period, came as the result of the depopulation of the rural world, during the 1960s and 1970s, mainly as the result of the mass immigration of young people, at the age of compulsory military service, during the colonial war in Africa. This sequence of events contributed significantly to the change in the forest management paradigm, particularly with justification and acceptance as an alternative and almost unique solution to the proliferation of eucalyptus [57–59].

This development contributed to forests following a path of virtual self-management in the post-revolutionary period, since the lack of labor for forestry activities led to the abandonment of forest land. These lands became the scenario for the rural fires that have ever occurred, and which are an integral part of the Mediterranean forest, but which, due to the abandonment of the land and subsequently the lack of management of the forest area, led to an increase in the seasonal rural fires [60].

In Portugal, there has been a continuous growth of forests only interrupted in the most recent period, especially after 2010, most probably due to the occurrence of rural fires in the summer, which in recent years have reached very significant proportions. This growth was mainly due to the abandonment of agricultural areas, reflected in the conversion of these areas into zones of spontaneous growth and natural regeneration. This trend is justified by the existence of driving forces fostered by the economic exploitation and the importance of these areas for the rural populations. Forests are the basis of a sector of the economy that generates thousands of direct jobs [46]. This number has suffered a significant reduction over the last two decades, motivated mainly by the exodus verified from the populations of the interior to the coast, and for the near-extinction of activities like resination [61]. Despite these indicators, but with the increase in production that has occurred, an increase in labor productivity in the sector is suggested [43]. In the context of forest-based industries, i.e., the industries that obtain their raw materials from the forest and its by-products, the following are noteworthy:

- The sawmills industry has been witnessing a phenomenon of concentration, with the disappearance of small sawmills. It is estimated, however, that the total sales volume has been maintained. In 2009, it contributed to around 1.5% of total exports [62].
- The pulp and paper industry contributes about 4 thousand direct jobs, but its main evolution has been in increasing vertical integration in the sector, with higher production of paper and paper, which leads to a notable increase in the value of the product, a trend which is still increasing. It is the second sector with the national highest value added and corresponds to 5% of national exports [57,63].
- The cork industry represents an important fraction of the national external trade, with around one third of the total exports of products of forest origin. The number of companies in this sector was 685 in 2018, with more than 8 thousand direct jobs [64–66].

However, despite all the difficulties and problems that exist in Portuguese forests, the impact that these have from the point of view of the national economy and, consequently, also from a social point of view, is very large. As evidence of this impact, it can be seen that the three largest national business groups have their industrial base in the forest and are world leaders in their sectors of activity, namely in the production of bleached pulp, cork products, and wood panels.

The importance of these issues is that Portugal still has a very high potential for the development of the forest value chain to be explored. Full utilization of the potential of the forest in the framework of a sustainable circular bioeconomy is an extraordinary opportunity to replace a growing number of products made from nonrenewable raw materials with products made from renewable resources. It is true that the rural fires of 2017 were catalysts for many changes already underway in the forest area, which will need time to generate effects. However, the focus was on risk management, which is important but also manifestly insufficient. The future Common Agricultural Policy (CAP) 2021–2027 represents the opportunity for strengthened funding, specific and targeted to these policies and approaches, but must be more ambitious. In this regard, the involvement of the State Budget must also be reinforced. Only with a clear and cohesive stake in the forest, with a combination of public and private investment, will national water availability and quality increase, will the rural economy be strengthened, will exports increase, and will climate changes be mitigated [67,68].

5. Conclusions

Portuguese forests play a fundamental role in the sustainable development of the country, since they are the basis of an entire value chain creation, which begins in the primary productive sector, but which mainly has as a destination the export of products with high added value, such as those derived from cork or bleached pulp.

Management based on the sustainability of the resource allows the rural environment, where forests are inserted, to be able to establish populations, creating the conditions for them to thrive and contribute consistently to the creation of value and wealth for the country, and to alleviate imbalances between urban and rural areas.

However, it is necessary for the forest management policies undertaken in the period following the revolution of 25 April 1974 to be reviewed and adapted to the new reality, be it the supply of raw materials for industry, or the fight against rural fires, or an increasingly important adaptation to the phenomenon of climate changes, where the management perspective cannot be purely economic but must include the other components of sustainability, that is, the social and the environmental aspects.

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CHAPTER 2 – Framework

Chapter Index

climate

Article

The Evolution of Climate Changes in Portugal: Determination of Trend Series and Its Impact on Forest Development

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Abstract: Climate changes are a phenomenon that can affect the daily activities of rural communities, with particular emphasis on those directly dependent on the agricultural and forestry sectors. In this way, the present work intends to analyse the impact that climate changes have on forest risk assessment, namely on how the occurrence of rural fires are affecting the management of the forest areas and how the occurrence of these fires has evolved in the near past. Thus, a comparative analysis of the data provided by IPMA (Portuguese Institute of the Sea and the Atmosphere), was carried out for the period from 2001 to 2017 with the climatic normal for the period between 1971 to 2000, for the variables of the average air temperature, and for the precipitation. In this comparative study, the average monthly values were considered and the months in which anomalies occurred were determined. Anomalies were considered in the months in which the average air temperature varied by 1 °C than the value corresponding to the climatic norm, in at least 50% of the national territory. The same procedure was repeated for the variable precipitation, counting as anomaly the occurrence of a variation in precipitation of 50%, also in 50% of the national territory. Then the calculation of the moving averages for cycles of 3, 5 and 7 periods were applied, and the trend lines were projected. Subsequently, the relationship between the results obtained and the occurrence of rural fires as well as the spatial distribution of forest area, species and structure were analyzed. From the results obtained it was possible to confirm the existence of a tendency for the occurrence of climatic anomalies, highlighting the occurrence of an increasing number of months with temperatures higher by at least 1 °C. It was possible to foresee the relation between the occurrence of rural fires and the periods of anomaly and absence of precipitation. From the results obtained it is also possible to infer that, analyzing the tendency for these phenomena to occur, it can be necessary to change the "critical period of rural fires", since it is verified that what is currently in use does not covers the entire period where anomalies occur and where large-scale rural fires potentially can happen.

Keywords: climate changes; Portuguese forest; rural fires; pests; invasive species

1. Introduction

The study of the climate is a complex field of investigation presently in great evolution, mainly due to the number of factors that can intervene in it, such as temperature, precipitation, sea currents and solar radiation, among others. These factors interact directly with the energy balance of the planet, provoking variations in different time scales, e.g. from tens to thousands or even millions of years, which make Earth's climate never static [1–3].

Climate changes can be defined as global variations of the Earth's climate, due to natural causes, but also to the action of Man [4]. Climate changes occurs at very different times and over all climatic parameters, such as temperature, precipitation, cloudiness, and so on. The designation "greenhouse effect" is applied to the phenomenon of retention of solar radiation by Earth's atmosphere through a layer of gases called "greenhouse gases". Without them life as it is known would not be possible, since the planet would be too cold [5].

Among these gases are carbon dioxide, nitrogen oxides and methane, which are produced mainly by industry, agriculture and the combustion of fossil fuels. The industrialized world contributed to increase the concentration of these gases by about 30% during the 20th century, when, without human action, nature was able to balance these emissions [6]. Today, there is a consensus about the idea that the current model of energy production and consumption is generating global climate changes, which in turn will cause serious impacts both on planet's environment and on socioeconomic systems [7].

In the distant year of 2001, the Third Assessment Report of the Intergovernmental Panel on Climate changes (IPCC) highlighted the evidence provided by observations of physical and biological systems showing that regional changes in climate, more specifically the increases in temperatures, were affecting different systems in several parts of the planet [8]. The report definitively stated that there were mounting evidences of the existence of climate changes and its derived impacts. However, the temperature increased by about 0.6 °C during the 20th century [9].

More recently, in 2013, the IPCC Summary for Policy Makers stated that "man's influence on the climate is obvious. This is evident from the growing concentration of greenhouse gases in the atmosphere, and it is extremely likely that human influence is the dominant cause of warming since mid-20th century. The continuous emission of greenhouse gases will cause further warming and changes in all climatic components of the planetary system. Limiting climate changes will require a substantial and sustainable reduction in the production and emission of greenhouse gases" [10]. Climate changes affects everyone on the planet indiscriminately. The potential impact is huge with predictions of lack of potable water, major changes in food production conditions and rising mortality rates due to floods, storms, droughts and heat waves [11].

Climate changes are not only an environmental phenomenon, but also have profound economic and social consequences. The poorest countries, which are least equipped to deal with rapid changes, will suffer the worst consequences. Extinction of animals and plants is expected as habitats will change so sharply that many species will not be able to adapt in time to survive. The World Health Organization (WHO) warned that the health of millions of people can be threatened by increased malaria, malnutrition and diseases [12,13].

Portugal, because of its geographical situation and socioeconomic characteristics, is very vulnerable to climate changes. As a consequence, even if there are uncertainties that do not allow the expected climate changes to be quantified with sufficient precision, the information validated so far is sufficient to take immediate action, in accordance with the so-called "Precautionary Principle", which to is made reference in Article 3 of the United Nations Framework Convention on Climate Change (UNFCCC) [14]. Inertia, delays and the irreversibility of the climate system are very important factors to be taken into account and, the longer it takes to start action, more the effects of increasing concentrations of greenhouse gases will be less reversible [15].

Climate change presents major challenges for the Portuguese forestry sector. The effects of climate changes on forest ecosystems in Portugal are already evident in many respects. Anticipated impacts of future climate scenarios indicate a progressive intensification of these effects as the 21st century progresses, e.g., in the distribution of forest formations, structural and functional changes, in certain parameters of forest health, greater vulnerability to extreme weather events and rural fires, and a change in the flow of environmental goods and services that forests provide [16].

The interactions between the forest area and the problem of climate changes must be analyzed from two perspectives. On the one hand, it is necessary to contemplate what the forests can bring to the reduction of this problem, being a path to mitigation, and on the other hand, what impact climate changes can have on forests, analyzing their adaptation and evolution [17].

These interactions are not independent and are affected by complex interconnection and cause-effect processes. For example, the importance of forests to mitigate CO_2 concentrations can be affected if the impact of climate changes reduce their storage capacity through growth and development constraints, or increases the problem of rural fires. In other words, it is necessary to define and apply tools to manage forests more efficiently, to tackle the problem of climate changes, interlinking adaptation and mitigation, with a view to adaptation in order to mitigate its effects and consequences [18,19].

In Portugal, forests occupy approximately 3.2 million hectares, about 35% of the total area of the country [20]. Portuguese forests provide many benefits and services, including clean water and air, recreational and leisure spaces, wildlife habitats, carbon sequestration and storage, climate regulation, and a variety of forest products with a large impact on the economy [21,22].

Climate influences the structure and function of forest ecosystems and plays a key role in forest health. A changing climate can intensify many of the threats to forests, such as the outbreak of pest outbreaks, fires, drought and the very development of populations there [23]. Climate changes directly and indirectly affect the growth and productivity of forests through changes in temperature, precipitation, climate and other factors. In addition, high levels of carbon dioxide can also affect plant growth. These changes influence the complex forest ecosystems in various ways [24].

Together with the impacts resulting from the effects of climate changes, forests face impacts due to the development of land management, namely due to their use and occupation, periodic rural fires and atmospheric pollution. Although it is difficult to separate the effects of these different factors, the combined impact is already causing changes in Portuguese forests. As these changes are expected to continue in the coming decades, some of the economic aspects provided by forests may be compromised in the short term [25].

This review article is intended to approach climate changes, starting from the global perspective and then to deal specifically with the Portuguese situation, from the point of view of impacts. Following sections deal specifically with the evolution of the climate in Portugal, with the objective of understanding how these variations can influence the development of the forest. In this way, an analysis of the current state and the development of the climate in the last years is presented, both in terms of the evolution of the average air temperature and precipitation evolution. An analysis is also made of the effects of the changes and their relationship with the occurrence of rural fires in Portugal, with particular attention to the period 2001 to 2017, and to the way in which these occurrences interfere in the development and evolution of forests. Finally, an analysis is made of the impacts of climate changes and its consequences on Portuguese forests, in particular due to the increase in the occurrence of rural fires, pests and occurrence of forest invasive species.

2. Impact of Climate Changes in Forest Production

2.1. Forest Growth and Productivity

There are several aspects related to climate changes that are most likely to significantly affect the growth and productivity of forest species. Examples of such factors are the rise in temperature, changes in precipitation levels and increases in the concentration of carbon dioxide [26].

The rise in temperature generally increases the duration of a plant's growing season. This factor also contributes to the change in the geographic dispersion of some tree species. In this way, the habitats of some types of trees tend to move to the north or to higher altitudes. Other species will be at risk locally or regionally if the conditions in their current geographical ranges are not the most appropriate. For example, species that currently exist only on top of mountains in some regions may disappear as the climate warms up as these species cannot evolve to a higher altitude [27].

Climate change is most likely to increase the risk of drought in some areas and the risk of extreme rainfall and flooding in other regions [28]. Increased temperatures change the defrosting time, affecting the seasonal availability of water. Although many trees achieve up to a certain degree of drought, rising temperatures can make future droughts more damaging than they have in the past. In addition, drought increases the risk of rural fires, since dry trees and shrubs provide fuel for the fires. Drought also reduces sap trees' ability to produce sap, which protects them from destructive insects and disease [29].

Carbon dioxide is needed for photosynthesis, the process by which green plants use sunlight to grow. With sufficient water and nutrients, increases in atmospheric CO_2 concentration may allow trees to have higher growth rates, which may alter the distribution of tree species. Growth will be higher on nutrient rich soils, with no water limitations, and will decrease with reduced fertility and water supply [30].

2.2. Pests, Invasive Species and Rural Fires

Climate changes can change the frequency and intensity of negative impacts on the forest, such as pest outbreaks, invasive species proliferation, rural fires and storm surges. These disturbances can reduce forest productivity and change the distribution of forest species. In some cases, forests may recover from a disturbance, but in other cases, existing species may evolve or disappear. In these cases, new plant species that colonize a given area create a new type of forest [31].

According to the opinion of several authors [32–34], with temperatures rising as the climate changes and warms, insects will become more active, and consequently more ravenous and abundant, increasing the likelihood of occurrence of insect pests. In this way damage to crops, both agricultural and forestry, is bound to increase [32]. This argument gains strength, as the increase in temperature accelerates the metabolism and reproduction of insects. The same authors estimate that each degree of increase in temperatures will mean increased damage in crops of 10% to 25% [32].

Unlike mammals and birds, insects heat or cool according to their environment. When an insect warms up, its metabolism accelerates. The faster you burn energy, the more voraciously the insect feeds and the sooner you can reproduce. The analysis of this information has allowed researchers to conclude that the growth rates of the populations are not very different among the different types of insects, allowing the development of a mathematical model that simulates the growth of the insect populations. This simulation allows us to infer the damage caused by these same populations of insects in the crops, both agricultural and forestry [32,34].

Tropical insects generally are already close to the upper limit of their temperature tolerance, so it can be concluded that it will not be in these regions that the greatest variations in insect populations will surely be observed. In areas with a more temperate climate, insects can significantly accelerate their activity, causing more damage to the crops. Variations in temperature may encourage or discourage insect species from invading new territories. Temperatures can also affect the parasites that attack the same insects that attack the crops, so the end result will greatly depend on the ability of all stakeholders to evolve and adapt to the new reality [32,35].

A number of biotic and abiotic agents have been identified in Portugal that are capable of causing physiological imbalances responsible for changes in tree development and that may be associated with the high frequency with which rural fires occur, which may lead to the onset of pests and diseases. Table 1 presents some of these pests that constitute major sanitary problems for the Portuguese forest.

The xylophagous or subcortical insects that attack the trunk can be considered as the most serious pests, since they block the circulation of sap, putting at risk the survival of the tree. Some of these insects also have the ability to inoculate agents that contribute to the weakening and death of trees [36]. Insect attacks on leaves usually do not jeopardize tree survival (with the exception of very severe attacks on young stands), as the young tree has been completely stripped of needles, leading to the tree's death. In other situations, for example with older and larger trees, canopy regeneration may occur, although it may show a decrease in its annual growth rate, since the energy reserves will be channeled for the renewal of the foliage [36].

Table 1. Main pests of the forest in Portugal (adapted from [36]).

Forestry Species	Scientific Name of the Pest
Eucaliptus	*Gonipterus platensis* *Phoracantha semipunctata*
Cork oak and holm oak	*Lymantria dispar* *Periclista* spp. *Tortrix viridana* *Curculio elephas* *Cydia splendana* *Coroebus undatus* *Coroebus florentinus* *Platypus cylindrus* *Xyleborus* spp.
Maritime pine and stone pine	*Thaumetopoea pityocampa* *Pineus pini* *Cinara maritima* *Leucaspis* spp. *Pissodes validirostris* *Dioryctria mendacella* *Leptoglossus occidentalis* *Orthotomicus erosus* *Tomicus* spp. *Ips sexdentatus* *Dioryctria sylvestrella* *Pissodes castaneus* *Monochamus galloprovincialis*

This situation is more critical in the resinous species since its leaf surface is renewed in a slower way than in the hardwood species. However, it is the pests and diseases introduced in Portugal that cause the most damage to the forest. This is an example of the introduction of the woody pine nematode (*Bursaphelenchus xylophilus*) in 1999, which is currently the most serious forest health problem in Portugal, and is responsible for enormous economic losses, not only due to the dead pine trees, but also due to the strong restrictions on the export of pinewoods [36].

Eucalyptus also suffered from the introduction of exotic species, such as mortality caused by the eucalyptus borer (*Phoracantha semiounctata*) in the late 1990s, mainly in Beiras and Alentejo and, more recently, the damage caused by the defoliant weevil in the North and Center regions [36].

Recently, other exotic insects have been registered in Portugal, such as the eurasian golden-bug (*Thaumastocoris peregrinus*) and the chestnut-horned wasp (*Dryocosmus kuriphilus*) [37]. Its medium and long-term impact in the national territory is not yet known, but because of the risk of being an emerging pest, action plans have already been implemented for its control [36]. Lack of natural controls such as predators or pathogens, as well as the fact that tree defenses are unsuitable for these harmful agents, may allow insects to spread. Climate changes could contribute to an increase in the severity of future insect outbreaks. Rising temperatures may allow some species of insects to develop more rapidly, alter their seasonal life cycles, and expand their activity to other latitudes than usual [38,39].

In 2017, rural fires consumed more than 442,000 hectares of forest in Portugal, causing 104 human casualties and more than 600 million euros in losses [40,41]. High temperatures and drought conditions during the early summer contributed to this tragic scenario [42]. The rural fires of 2017 were the largest catastrophe in the country in terms of the number of fatalities since the fateful floods of 1967 [43]. Rural fires cause a feeling of impotence in the population, which considers them almost a fatality intrinsic to the Portuguese forest, to the point of generalizing the expression "fire season", as if it were naturally part of the calendar as another season [44]. Since 2000, 200 people have died as a result of rural fires in Portugal [45].

As mentioned earlier, hundreds of thousands of hectares of forest have disappeared, accounting for more than half of the area burned in Europe in 2017 [46] and comprising a great historical landmark, since the fire decimated a significant part of the Pinhal do Rei in Leiria, from where the legend must have left the mythical wood that served to build the ships and caravels that led the Portuguese in the period of maritime expansion [44]. But it was not only the past that was destroyed, since the industrial and agricultural sectors were also largely hit, putting a high number of jobs at risk.

However, this event is not new and in 2017 it only reached the contours that it reached due to the absurd number of deaths and injuries, since in previous years similar phenomena were observed, except for the number of victims. The effect of climate changes is expected to contribute to increasing the extent, intensity and frequency of rural fires in certain areas of the country. Warmer spring and summer temperatures, coupled with reduced availability of water, dry woody materials in forests and increase the risk of rural fires.

Fires can also contribute to the very phenomenon of climate changes, as they can cause large and rapid releases of carbon dioxide into the atmosphere [47]. It is important to note that fire activity is not only determined by drought as a structural basis and by meteorology as the conjunctural basis of risk. The continued aridity has effects of greater temporal availability of all vegetation to burn, resulting in campaigns of continuous or extended fires, creating the conditions for large fires more easily and quickly than under the "normal" regime of situations [48].

The concept of "aridity" of fuel has been related in the USA with the increase in rural fires in size and severity [49]. This concept, as well that of fine fuel moisture content (FFMC) [50], is related to climate changes and contributes to the regime of extreme fires of the past gradually becoming the current normal fire regime [51]. Spring weather, and especially June weather conditions, led to very significant fuel "aridity" conditions. The months of June 2015–2017 along with the four-year period 2003–2006 were the hottest since record keeping, coinciding with years of larger fires [52]. There is, however, a significant difference between 2017 and the years 2003 to 2006, which means that in 2017 the concept of "aridity" of fuel has reached its maximum in Portugal by making a warm June to hot spring happen, what differentiates 2017 from the years of great fires of the recent past. As a result, in 2017 there was an advance of the first major fires of the year to June, when in the past they had always occurred in late July and early August. This change constitutes a clear impact of the effect of climate changes on contemporary fire regimes [53].

In the data presented in Table 2 it can be observed that the occurrence of rural fires has been a recurring situation in recent years. The table shows the area burned in fires from 1980 to 2017, as well as the number of ignitions occurred during the same period, in order to allow the correlation between the fires and the burning area and the annual costs caused by rural fires. From the analysis of the data it is possible to infer a tendency for the growth of the area burned in rural fires, mainly from the 90s, although this tendency has already occurred since the 80s, but with less significance. According to the Portuguese Nature and Forests Conservation Survey (ICNF) available data, the 10 years with the highest area burned all occurred after this period, including the peak year in 2017. This period coincides with many of the hottest years recorded throughout the country.

This type of occurrence, especially when it occurs simultaneously, can interact with one another, or with changes in temperature variation and amount of precipitation, to increase the risks for the occurrence of several impacts on the forests. For example, drought can weaken trees and make the forest more susceptible to rural fires or outbreaks of insect pests and diseases. Similarly, after the occurrence of a forest fire, the forest may become more vulnerable to insect pests and diseases. This permanent occurrence of rural fires in Portugal, in addition to the environmental impact that is easily recognized, also has a very significant impact on the economic perspective.

In fact, as already mentioned, the trivialization of the "fire season" as if it were a seasonally repeatable period of the Portuguese year led to the inclusion of significant amounts of costs in the state budget for the prevention of rural fires, in addition to the creation of an increasingly modern and prepared device to combat the fires. Table 2 presents as well the costs related to the occurrence of rural fires from 1980 to 2017. From the simple analysis of the data, there is a progressive increase in costs associated with the growth of the burned areas. The amount presented represents the sum corresponding to the amount spent each year on the prevention, combat and costs associated with the damages caused by rural fires.

Table 2. Annual costs associated with rural fires (adapted from [20] and [54]).

Year	Nr. of Occurrences	Burned Area (m^2)	Total Costs (€)
1980	2349	44,251	€96,024,670
1981	6730	89,798	€194,861,660
1982	3626	39,556	€85,836,520
1983	4542	47,811	€103,749,870
1984	7356	52,710	€114,380,700
1985	8441	146,254	€317,371,180
1986	5036	89,522	€194,262,740
1987	7705	76,268	€165,501,560
1988	6131	22,434	€48,681,780
1989	21,896	126,237	€273,934,290
1990	10,745	137,252	€297,836,840
1991	14,327	182,486	€395,994,620
1992	14,954	57,012	€123,716,040
1993	16,101	49,963	€108,419,710
1994	19,983	77,323	€167,790,910
1995	34,116	169,612	€368,058,040
1996	28,626	88,857	€192,819,690
1997	23,497	30,535	€66,260,950
1998	34,675	158,369	€343,660,730
1999	25,473	70,613	€153,230,210
2000	34,107	159,605	€433,000,000
2001	26,947	112,312	€319,000,000
2002	26,576	124,619	€394,000,000
2003	26,219	425,839	€1,303,000,000
2004	22,165	130,108	€402,000,000
2005	35,824	339,089	€756,746,827
2006	20,444	76,058	€132,001,898
2007	20,316	32,595	€37,109,004
2008	14,930	17,565	€22,371,685
2009	26,136	87,421	€86,259,214
2010	22,026	133,091	€183,911,947
2011	25,222	73,829	€80,557,921
2012	21,179	110,232	€196,227,660
2013	19,294	152,690	€208,337,840
2014	7067	19,930	€27,503,169
2015	15,851	64,412	€119,406,200
2016	13,079	160,490	€460,000,000
2017	16,981	442,418	€616,000,000
Total		4,419,166	€9,589,826,075

This phenomenon of rural fires in Portugal, which it is now beginning to be understood can be boosted by climate changes, does not however originate in these changes or even natural causes in the overwhelming majority of occurrences. Nowadays, the cause of the origin of the great majority of the rural fires is already investigated, being therefore possible to refute the thesis of the natural origin for these occurrences.

Both the ICNF and the Nature and Environment Protection Survey (SEPNA), belonging to the National Republican Guard (GNR), have the human and technical capacity to analyze the causes that caused a certain ignition and disseminate the results of the investigations in documents that are available at their respective websites, which can be followed at the addresses, respectively (www.icnf.pt and http://www.gnr.pt/atrib_SPENA.aspx). From the analysis of these data we obtain the results that are presented in Table 3.

Table 3. Causes of rural fires investigated by National Republican Guard/Nature and Environment Protection Survey (GNR/SEPNA) in 2016 (adapted from [20]).

Causes	Percentage of Total Occurrences
Undetermined	34.7%
Use of fire	25.2%
Arson	21.6%
Re-ignition of rural fires	13.6%
Accidental	3.5%
Natural	0.7%
Structural	0.6%

From the analysis of the data presented in Table 3, it can be observed that in the vast majority of cases, rural fires have an accidental, negligent or willful origin, origin in human activity, and the role of natural phenomena to which responsibilities, are clearly very insignificant. This group includes, for example, the occurrence of dry thunderstorms, very frequent in the summer. However, as shown in the previous table, with a very insignificant weight in the overall number of occurrences. Among all the frequent causes, it continues to be the "use of fire", mainly in the form of burnings to eliminate agricultural and forest residues, that is the main cause for the occurrence of rural fires (Figure 1).

Figure 1. Panoramic picture taken on 12/5/2017 from ESA—Ponte de Lima School of Agriculture of the Polytechnic Institute of Viana do Castelo (north Portugal), where it is possible to observe 9 fires in a rural environment occurring simultaneously.

3. Evolution of Climate Changes in Portugal

3.1. Framework

As previously mentioned, climate can be defined as the set of long-term meteorological conditions prevailing in a given area. Thus, in this perspective, the average values of the climatic variables of a given location will be more representative according to the time interval used in the analysis, thus constituting a time serie. In this way, the same results are not obtained when comparing a time interval of one year with one of 10 years, or one of 100 years. It is important to have long time series of data to analyze the variations and the evolution of the climate. For example, the Portuguese Institute of the Sea and the Atmosphere (IPMA), has available series of meteorological data dating back to 1865 [55].

The World Meteorological Organization (WMO) agreed that climate characterization is done by analyzing the mean values of the various climatic elements over a period of 30 years [56,57]. This period is the normal value of a climatic element and represents the average value corresponding to a sufficiently long number of years to be assumed to represent the predominant value of that element at the site under consideration [58,59]. Similarly, the WMO designates the statistical values obtained for periods of 30 years, starting in the first year of each set of years (1901–1930, 1931–1960, 1961–1990, 1991–2020) [60]. These are the reference normals or average representative values, however, can be calculated and used climatological normals based on intercalary periods, for example periods like 1951–1980 or 1971–2000 [55].

The Portuguese Institute of the Sea and Atmosphere (IPMA) provides online information on the climatological normal of 21 meteorological stations for the period 1971–2000, including monthly and annual values of the main climatic elements. In the same website are also available the average values of air temperature and total precipitation. For the two climatic parameters selected, average air temperature and precipitation, IPMA provides information on the occurrence of anomalies by creating maps of isolines representing, in the case of average air temperature, areas where the air temperature exceeded (positive or negative) the values of the last climatic normal (period from 1971 to 2000). Likewise, for precipitation, isoline maps are also presented, thus representing percentage of the amount of precipitation occurred compared to normal climatic conditions (period 1971 to 2000).

Subsequently, new maps of isolines based on the previous ones, made available by the IPMA website, were constructed, which were simplified in order to facilitate the reading and counting of the number of anomalies that occurred, both for the average air temperature and for the precipitation. After counting the anomalies in the period from 2001 to 2017 for the two parameters selected, tables were elaborated presenting the data. For the verification of the existence of a trend of occurrence of events and to allow a better visualization of the results, a moving average model was applied, because this method facilitate the smoothing of the plotting of the data allowing an easier visualization of the eventual trend.

3.2. Air Temperature Anomalies

The most well-known and referred parameter when it comes to the subject of climate changes is surely the rise of air temperature. If on the one hand the scientific community addresses other parameters with the same concern and capacity for analysis, civil society refers to this particular issue, often without understanding its real effects, but mainly because it is the most approached by the media. It is a rare day when no news comes out in all kinds of media that do not allude to "global warming" and the "greenhouse effect", or very specifically to its effects and consequences anywhere in the world, such as occurrences of rural fires, hurricanes, floods, long periods of drought, rising sea levels or changing monsoon cycles.

Thus, this section analyzes the occurrence of anomalies in the average air temperature. In this particular case, the occurrence of an anomaly is considered whenever the average monthly temperature exceeds 1 °C, compared to normal climatic conditions during the period 1971–2000. Based on this analysis, isoline maps were constructed, as the presented in the example of Figure 2, which visually indicate which regions of the country have exceeded +1 °C (colored in red), −1 °C (colored in blue) and which were similar to normal climatic (colored in green). An abnormal month is considered when at least 50% of the national territory has been subjected to temperature values above or below 1 °C compared to normal climatic conditions (period 1971–2000).

Table 4 shows the anomalies observed in the period between 2001 and 2017. As can be seen, there was a significant set of anomalies in all the constituent years of the period, with a maximum of anomalies of 7 occurring in 2017 2005, 2006, 2009, 2015 and 2017. The lowest number of anomalies was reached in 2004 and 2007, with 3 occurrences. Based on these data, it is necessary to determine the existence of a tendency for an increasing number of anomalies, that is, to determine if the number of anomalies occurring in the period between 2001 and 2017 shows a tendency to occur in some sense. For this inquiry the simple moving average method was used [61].

The determination of the simple moving average of a set of n elements is obtained by calculating the unweighted averages of the subsets of n elements in a given set of data. For example, given a set of n elements $p_1, \ldots, p_n$, the first element of the moving average is given by Equation (1):

$$Mn = \frac{p_1 + \ldots + p_n}{n} = \frac{1}{n} \tag{1}$$

the second is given by Equation (2):

$$Mn' = \frac{p_2 + \ldots + p_{n+1}}{n} = \frac{1}{n}\sum_{i=2}^{n+1} p_i \tag{2}$$

or even by Equation (3):

$$Mn' = Mn + \frac{p_{n+1}}{n} - \frac{p_1}{n} \tag{3}$$

and so on until $p_{n-n+1}, \ldots, p_n$.

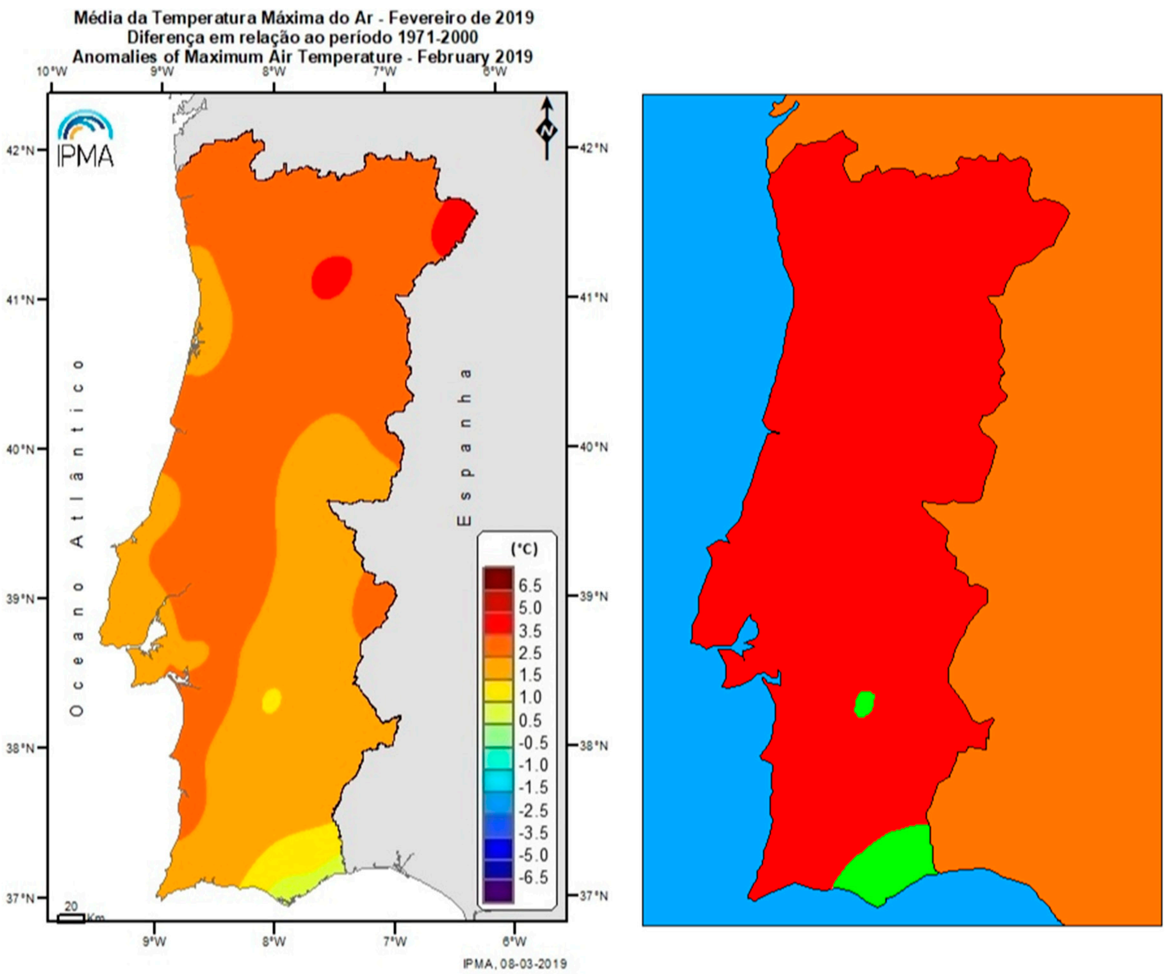

Figure 2. Example of the creation of isolines maps for the anomalies of in February in the year 2019. In the left part is the image obtained at the Portuguese Institute of the Sea and the Atmosphere (IPMA) website and in the right side is the image created from the first one.

The same Table 5 presents the results of the application of the simple moving average method and in Figure 3 the trend lines are presented. In this particular situation the method was applied for 3, 5 and 7 periods, since it was understood that for the number of data available, it would be sufficient.

The application of the periods consists in the aggregation of data groups according to the period used, and in the performance of the average of that group, the result obtained corresponds to the average element of the group. For example, for an average of three periods, the first three years, 2001, 2002 and 2003 are selected, and the average number of occurrences for these three years are determined. The final result is assigned to the middle element, in this case it is the year 2002. Then the operation was repeated for the group of the next three elements, 2002, 2003 and 2004, and so on.

Table 4. Results obtained from the application of the simple moving average method.

Year	Nr. of Occurrences	3 Periods Average	5 Periods Average	7 Periods Average
2001	5			
2002	5	5		
2003	5	4	5	
2004	3	5	5	5
2005	7	6	5	5
2006	7	6	5	5
2007	3	5	6	5
2008	4	5	5	5
2009	7	5	5	5
2010	5	6	5	5
2011	5	5	5	5
2012	4	5	5	6
2013	5	5	5	5
2014	6	6	6	6
2015	7	6	6	
2016	6	7		
2017	7			

Table 5. Distribution of climatic anomalies by the months of the constituent years of the period under analysis.

Year	J	F	M	A	M	J	J	A	S	O	N	D
2001	a	a	a	a		a						
2002	a	a	a	a								a
2003			a		a	a		a	a			
2004	a					a	a					
2005			a	a	a	a	a	a		a		
2006				a	a		a	a	a	a	a	
2007		a		a	a							
2008	a	a		a		a						
2009			a		a	a		a	a	a	a	
2010				a		a	a	a	a			
2011				a	a	a			a	a		
2012			a		a	a			a			
2013	a						a	a	a	a		
2014	a	a			a				a	a	a	
2015				a	a	a	a			a	a	a
2016	a					a	a	a	a	a		
2017		a		a	a	a	a	a		a		
Total	7	6	6	10	10	12	8	8	9	9	4	2

For the calculation of the means of five and seven periods, the procedure is similar, but now, instead of selecting three elements, five or seven will be selected, repeating the operation for all the elements of the sample. The higher the number of data available, more averages with different periods can be calculated, the data being analyzed as linearly as possible. It is in this way that one can determine if there is a growing or decreasing tendency of the occurrence of a given event (Figure 2).

In the previous figure is showed the projection of the data previously presented in Table 1. As can be seen, the real data or the total occurrences, represented by the blue line, allow the creation of a trend line and indicate by itself a perspective increase in the number of occurrences. However, with the application of the simple moving averages method, it is verified that the lines corresponding to each of the averages, the average of three periods being represented by the brown line, the average of the five periods represented by the green line and the average of seven periods represented by the purple line, indicate in a much more visible way an increasing tendency for the occurrence of climatic anomalies. This fact is even more noticeable when one observes the lines or lines of trend, which clearly indicate an increasing trend towards a more frequent occurrence of this event.

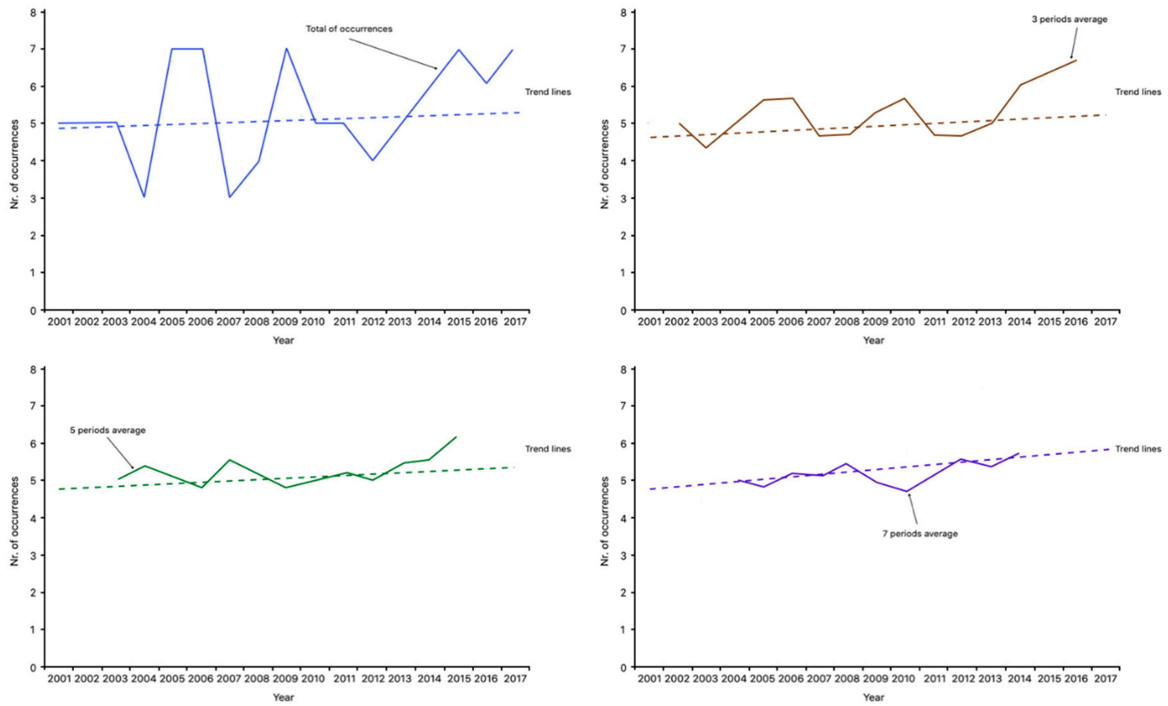

Figure 3. Trend lines. As can be seen in the figures, the lines indicate an increasing tendency for anomalies to occur, allowing it to be inferred that, over the years, an increasing number of anomalies can be expected to occur.

In addition to this verification of the tendency for a given event to occur, in this case the occurrence of climatic anomalies, it is also necessary to verify the probability of occurrences occurring in one month to the detriment of another, since this seasonality, associated to the occurrence of precipitation and to the biological cycles of plant growth may be determinant for the increased risk of occurrence of rural fires, as well as for their degree of intensity and severity.

Table 5 presents the distribution of climatic anomalies by the months of the constituent years of the period under analysis. As can be seen in the data presented in Table 5, although there is a dispersion for all the months of the year, since climatic anomalies occurred in all months of the year without exception. Over the last 17 years under analysis in this study, there is a higher concentration of these events in the spring and early summer months (April, May and June), so if factors are also anomalous in the following months, summer and autumn, also associated to the occurrence of precipitation anomalies, a strong probability of occurrence of ideal conditions for the outbreak of rural fires of great intensity and severity.

As can be seen, there is also a strong tendency for air temperature anomalies to occur during the summer and autumn months, so it can be said that the probability of repeating situations such as those occurring in 2017, favorable for the outbreak of fires in summer and autumn, is very high.

3.3. Precipitation Anomalies

Similar to the methodology used for the previous section, maps of isolines were created on the maps made available on the IPMA website (www.ipma.pt). In these maps, the zones of the country where precipitation was at least equal to that of the normal climatic period used in this study, the period 1971 to 2000 were defined as an anomaly when in a given month, in at least 50% of the continental national territory, precipitation was lower than that occurred in the period of normal climatic conditions.

Table 6 shows the precipitation anomalies observed in the period between 2001 and 2017. As can be seen, there was a significant set of anomalies in all the constituent years of the period, with a maximum of 11 anomalies occurring until 2017, in the years of 2015 and 2017, but in 2008 there were 10 anomalies, and in the years 2004, 2007, 2009 and 2012, there were 9 anomalies. The lowest number of anomalies was reached in the years 2006 and 2014, with 5 occurrences. Table 6 presents the results of the application as well of the simple moving average method and in Figure 4 the trend lines are presented, using the same methodology described in the previous section. Also, in this situation the method was applied for 3, 5 and 7 periods, since it was understood that for the number of data available, it would be sufficient. Based on these results the graphic presented in Figure 4 was constructed, where the trend lines are also projected, and the projection of data previously presented in Table 3 are shown.

Table 6. Results obtained from the application of the simple moving average method.

Year	Nr. of Occurrences	3 Periods Average	5 Periods Average	7 Periods Average
2001	6			
2002	7	6		
2003	6	7	7	
2004	9	8	7	7
2005	8	7	7	8
2006	5	7	8	8
2007	9	8	8	8
2008	10	9	8	8
2009	9	8	8	8
2010	6	7	8	8
2011	7	7	8	8
2012	9	8	7	8
2013	8	7	8	8
2014	5	8	8	8
2015	11	8	8	
2016	7	10		
2017	11			

As can be seen, the actual data or total counted occurrences, represented by the blue line, allow the creation of a trend line and indicate in itself a growth perspective of the number of occurrences. However, with the application of the simple moving averages method, it is verified that the lines corresponding to each of the averages, the average of three periods being represented by the red line, the average of the five periods represented by the green line and the average of seven periods represented by the purple line, indicate in a much more visible way an increasing tendency for the occurrence of climatic anomalies.

This fact is even more noticeable when trend lines are analyzed, which clearly indicate an increasing trend towards a more frequent occurrence of this event, similar to what had already happened in the previous section, in the analysis of air temperature anomalies.

As can be seen in Table 7, there is a dispersion of the occurrence of anomalies for all the months of the year, since occurred climatic anomalies in all months of the year without exception. Over the last 17 years under analysis in this study, there is a greater concentration of these events in the spring and early summer months (April, May and June), so if factors are also anomalous in the following months, summer and autumn, also associated with the occurrence of precipitation anomalies, there is a strong probability of occurrence of ideal conditions for the outbreak of rural fires of great intensity and severity. It also appears that the occurrence of periods with precipitation at levels lower than usual would occur more and more frequently and can be said that the trend of the period between 2001 and 2017 is the repetition of periods of low precipitation.

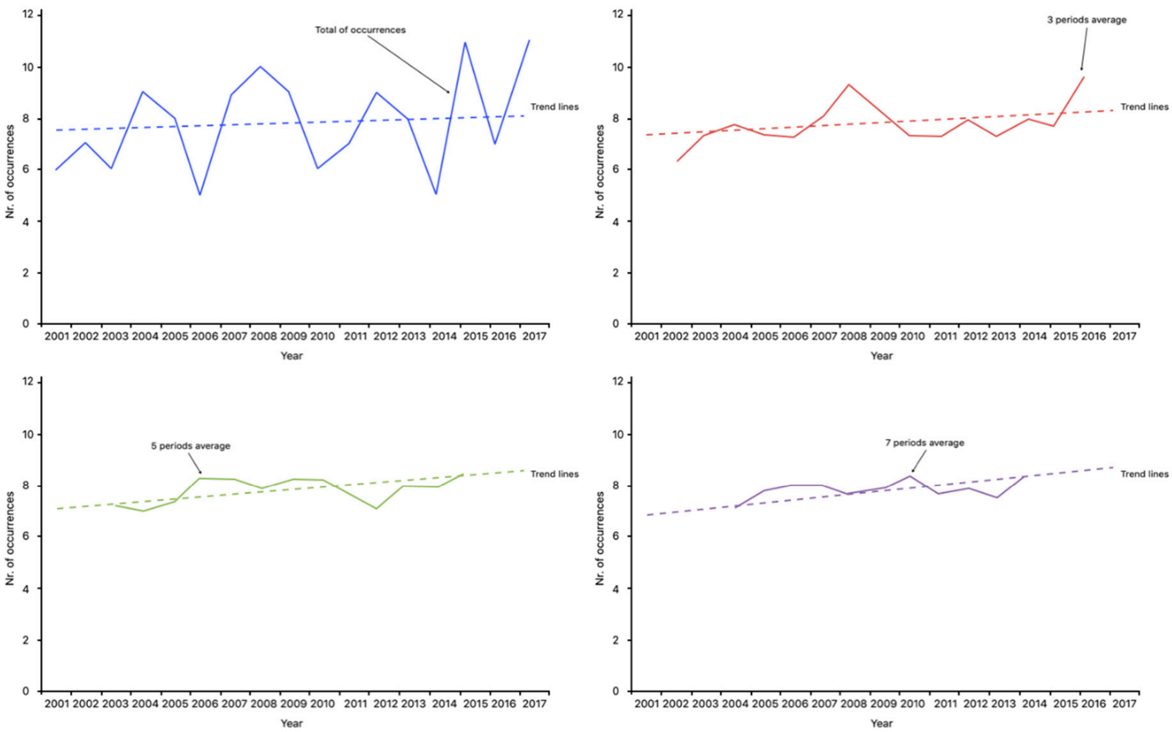

Figure 4. Trend lines. As can be seen in the figures, the lines indicate an increasing tendency for anomalies to occur, allowing it to be inferred that, over the years, an increasing number of anomalies can be expected to occur.

Table 7. Distribution of climatic anomalies by the months of the years of the period under analysis.

Year	J	F	M	A	M	J	J	A	S	O	N	D
2001	a		a			a	a				a	a
2002	a	a		a	a	a	a	a				
2003		a			a	a	a		a			a
2004	a	a	a	a		a	a		a		a	a
2005	a	a		a		a	a	a	a			a
2006	a	a		a	a							a
2007	a	a	a	a	a		a			a	a	a
2008	a	a	a			a	a	a	a	a	a	a
2009		a	a	a	a		a	a	a	a	a	
2010				a	a		a	a	a		a	
2011	a				a	a	a		a	a		a
2012	a	a	a	a	a	a	a	a				a
2013		a		a	a	a	a	a			a	a
2014			a		a	a		a				a
2015	a	a	a	a	a	a	a	a	a		a	a
2016			a			a	a	a	a	a		a
2017	a	a		a	a	a	a	a	a	a	a	a
Total	11	12	9	11	12	13	15	11	10	6	9	14

As can be observed, there is also a certain tendency for precipitation anomalies to occur during the spring and summer months, so it can be said that the probability of repeating situations such as those occurring in 2017, with very favorable conditions for the outbreak of rural fires in summer and autumn is very high, especially when the conditions previously discussed are combined.

However, these considerations still have to be validated through the analysis of a longer time period, since the use of a range composed of only 17 years seems manifestly short so that definitive conclusions can be drawn on the evolutionary tendency of the climate. Several authors indicate in their work that a period of less than 30 years may not be representative to justify an evolutionary analysis of the climate [62–64]. Many point to the analysis of time intervals of 30, 50, or even more years. However, there are other authors who point to the use of more restricted time windows, in order to allow the analysis of short duration sensitivity, which may somehow indicate trends in a given direction, for one or more variables [4,65].

Notwithstanding the fact that this is not the most appropriate conclusion, in order to verify if there is an effective trend of climate change, the data indicate a tendency for an increasing number of climate anomalies, both associated with monthly air temperature average, and to the monthly average precipitation, when compared to the normal period 1971–2000. A good possibility for an expedited confirmation of the existence of a trend in time series is through the use of the non-parametric Mann–Kendall test, suggested by the WMO to evaluate the trend in time series of environmental data.

The non-parametric Mann–Kendall test is commonly employed to detect monotonic trends in series of environmental data, climate data or hydrological data [66]. The null hypothesis, H_0, is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis, H_A, is that the data follow a monotonic trend. The Mann–Kendall test statistic is calculated according to:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(X_j - X_k\right) \tag{4}$$

where,

$$sgn(x) = \begin{cases} 1\ if\ x > 0 \\ 0\ if\ x = 0 \\ -1\ if\ x < 0 \end{cases} \tag{5}$$

The mean of S is E[S] = 0 and the variance, σ^2 is:

$$\sigma^2 = \left\{ n(n-1)(2n+5) - \sum_{j=1}^{p} t_j\left(t_j - 1\right)\left(2t_j + 5\right) \right\} / 18 \tag{6}$$

where p is the number of the tied groups in the data set and t_j is the number of data points in the j^{th} tied group. The statistic S is approximately normal distributed provided that the following Z-transformation is employed:

$$Z = \begin{cases} \frac{S-1}{\sigma}\ if\ S > 0 \\ 0\ if\ S = 0 \\ \frac{S+1}{\sigma}\ if\ S < 0 \end{cases} \tag{7}$$

The statistic S is closely related to Kendall's τ as given by:

$$\tau = \frac{S}{D} \tag{8}$$

where,

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{p} t_j\left(t_j - 1\right) \right]^{\frac{1}{2}} \left[\frac{1}{2}n(n-1) \right]^{\frac{1}{2}} \tag{9}$$

From the application of the Mann–Kendall test to the counted data of the anomalies occurring for mean air temperature and precipitation, summarized in Table 8 and in Figures 5 and 6, it can be inferred that there is in fact an increasing tendency for occurrence of this type of anomalies. Considering the hypothesis H0: there is no trend in the series, and the hypothesis Ha: there is a positive trend in the series, and since the calculated p-value is lower than the level of significance, we reject the null hypothesis H0 in favor of the alternative hypothesis Ha.

Table 8. Summary of data obtained from the Mann–Kendall test.

Series/Test	Kendall's τ	*p*-Value	Sen's Slope
Temperature anomalies	0.281	0.144	0.077
Precipitation anomalies	0.242	0.194	0.148

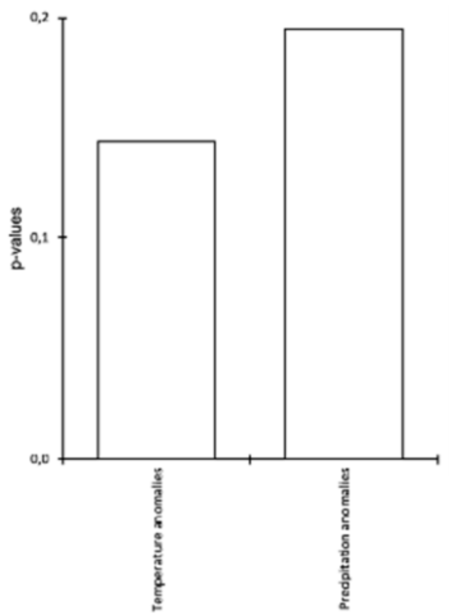

Figure 5. *p*-values.

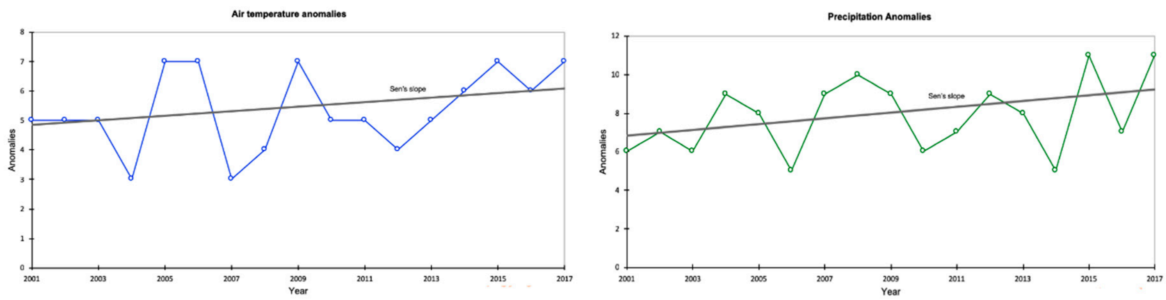

Figure 6. Sen's slope indicating the increasing probability for the occurrence of anomalies. As can be seen in the figures, the Sen's slope indicates an increasing trend for the occurrence of anomalies, allowing it to be inferred that, over the years, an increasing number of anomalies can be expected to occur.

4. Discussion and Conclusions

As stated previously, temperatures on Earth are suitable for life thanks to a natural process called the "greenhouse effect". When solar radiation reaches the atmosphere, part of it is reflected into space, and part of it passes and is absorbed by the Earth. This causes the Earth's surface to heat up. The heat is radiated out and absorbed by the gases present in the Earth's atmosphere, the so-called "greenhouse gases" (GHG) [67]. This process prevents the heat from disappearing, causing the temperature to rise to +14°C instead of −19°C. There are many greenhouse gases responsible for additional warming of the atmosphere, which are produced in different manners. Most come from the combustion of fossil fuels in cars, factories and the production of electricity. The gas responsible for most of the heating is carbon dioxide. Other gases that contribute to heating are methane, which is expelled by landfills and agriculture (especially from the digestive systems of large animals in intensive production), nitrous oxide from fertilizers, gases used for cooling in industrial processes and massive loss of forest area, otherwise they would store CO_2 [68,69].

Forests, which function as warehouses for greenhouse gases, help to mitigate the effects of climate change. However, the biological diversity of forests is also directly and indirectly affected by changing climatic conditions. These changes question the extent to which forests could continue to sequester greenhouse gases in the future [70].

The models that represent the ecosystems and their variations in the different climatic scenarios suggest that the changes will present a variety of impacts on the distribution of the forest populations, as well as on the impact on the function and composition of the ecosystems. In general, habitats are expected to move towards the poles and progress in altitude, conquering new territories [71].

With the change of the habitats, forest biodiversity will be forced to adapt and as a result, species composition in forests will likely change, and species and populations that are already vulnerable will become potentially extinct. In addition, with climate changes, there will be a greater incidence of extreme weather events, such as floods and droughts. These types of events will further affect forest populations and may make forests more prone to disturbances such as fires, invasive species, diseases and pests [72]. A mixed and preferably autochthonous forest stand, consisting of several different tree species with different ecological requirements and the ability to adapt to the expected changes in temperature, precipitation, frequency of storms and pests, will allow for continuous adjustments according to the climatic evolution [73].

The problem of climate changes has been addressed in a continuous way in Portugal, both by elements of the academic world, which are drawing attention to the causes and consequences of the phenomenon, but also by other sectors of civil society, in particular by the political sector, which has since some time initiated an ambitious program for the implementation of measures aimed at minimizing the negative impacts of climate changes in the country. Although they are still are taking the first steps in understanding the causes and consequences, it is assumed by the national and international scientific community that countries with Mediterranean climate characteristics may be the most affected by climate changes [16,74,75].

In this sense, a significant effort has been made in Portugal to implement measures that contribute to mitigating the harmful effects of climate changes, which at least begin to have international recognition. On 18 June 2018, TSF radio station on its website published a news item entitled "Portugal is second in a ranking on ambition in goals and measures to comply with the Paris Agreement on climate changes, being only exceeded by Sweden. The vast majority of the Member States of the European Union (EU) are failing to reach the targets of the Paris Agreement, and Portugal is among the few countries that have appealed to goals and policies more ambitious in the area of energy and climate, such as reducing greenhouse gas emissions". This information is the result of a study entitled "Off target: Ranking of European Union (EU) countries 'ambition and progress' in fighting climate changes", which determines member states' commitment to achieving energy policy and energy targets and the progress they are making in reducing greenhouse gas emissions and implementing programs for the use of energy from renewable sources and energy efficiency [76].

The planet's climate has undergone major changes for several decades. The IPCC report indicates that climate warming is evident and that most is probably due to the increase in GHG concentrations caused by human activities, such as the widespread use of fuels, the decomposition of urban or livestock waste and the changes in the occupation of the soil.

There is already irrefutable proof of this change. The temperature of the atmosphere at surface level has undergone a progressive warming from the beginning of the industrial era to the present day of approximately 0.6°C on average, with an even greater increase in some areas such as the poles or the Mediterranean region. The hottest years since recordings have occurred since 1990, as well as major seasonal changes, such as the decline of icy surfaces, rising sea levels, changes in the overall circulation flow of marine currents, and so on [77–79]. The frequency and severity of extreme weather events has increased. There is a more frequent occurrence of floods, heat and cold waves and periods of prolonged drought. An example of this is the news and constant warnings of hurricanes and storms of extreme force, which always cause high economic and personal damages.

There is a total consensus on the part of the scientific community when it comes to attributing to the increased concentration of GHG generated by human activities the greater responsibility for the phenomenon of climate changes. The reality is that without the natural presence of some of these gases in the atmosphere, such as water vapor and CO_2, creating the known greenhouse effect, Earth would be a very different place from what is known today, with average temperatures well below the current.

Since the beginning of the industrial revolution, when large quantities of fossil fuels began to be burned to meet the energy needs of industrial processes, so far, the amount of CO_2 in the atmosphere has increased progressively. Likewise, other anthropogenic GHGs also increased their concentration in the atmosphere considerably. Demographic growth and the current socio-economic model put great pressure on the self-regulating capacity of the atmosphere, which is leading to a situation close to its limits and, according to some scientists, likely to overcome them.

The main causes for GHG emissions vary according to the regions of the planet. Thus, in the northern hemisphere, the main causes are associated with energy production, industrial production and transportation, while in the southern hemisphere the main causes are associated with the change in land use, namely through the conversion of extensive forest areas into agricultural land or pastures.

It should be noted that in recent years there was an effort in the industrialized countries, with some success in some cases like Portugal, for the reduction in carbon dioxide emissions. The reasons for this reduction are the introduction of more efficient technologies, the use of renewable energies, the increasing weight of the services sector and the relocation of the most polluting companies to less developed countries. However, the steady growth of these industrialized economies, as well as the significant increase in emissions in other sectors, such as transport and the domestic sector, have made the total amount of GHG emissions of human origin increase considerably in recent years.

Forests like all other natural ecosystems are as susceptible to climate changes as other sectors (such as agriculture, for example, which are also highly vulnerable to climate and environmental changes). Unlike other sectors, where financial resources and technology can directly contribute to increasing the adaptive capacity of affected systems, natural forests depend on their own natural ability to adapt.

Adding to all this human pressure, pressure for development, and climate changes itself, it is highly likely that the ability of forestry systems to adapt to the new situation quickly and efficiently will be exceeded. It is expected that different forest systems will have different sensitivities to changes in climate. Therefore, it is important to take into account that the conservation of forests for other uses, and their ability to sequester carbon dioxide, can contribute predominantly to carbon dioxide emissions in the future if forest systems are affected by natural or human influences.

The way ecosystems respond to climate changes is usually guided by two paradigms: evolution and adaptation, as seen in previous sections. In the first one it is assumed that there will be a migration of ecosystems to other regions, almost intact, just looking for new locations where climatic and environmental conditions reproduce those where they currently are. The second paradigm assumes that as the climate and other factors change, ecosystems will change in the same location where they are today, which will interfere both in the variety of species and in their position in the ecosystem.

In addition to the intrinsic value of natural ecosystems, ecosystems of all kinds, from the most natural to the most intensively managed, offer a variety of benefits to society as a whole. Some of the products originating from these ecosystems enter the market and contribute directly to economic development. For example, forests are a source of raw materials for a number of industries, such as the production of biomass pellets, pulp production, the production of wood pellets and the production of furniture. Forest ecosystems also provide a number of benefits to society, such as their role in regulating water flows, preventing erosion, maintaining biodiversity and temporary storage of carbon, which can be as long as the longer the forest species and the more extensive the forestry operation recommended, for example, in the Portuguese case, using native species such as oaks, holm oaks or cork oaks.

Changes in soil cover caused by climate changes can have a number of impacts on these benefits, such as the ability of these systems to stabilize the landscape against erosion or sequester carbon dioxide. Even in regions where the amount of existing vegetation is expected to increase as a result of higher precipitation rates and increased growth due to the higher concentration of atmospheric carbon dioxide it can lead to an increase in the frequency and intensity of fires during a longer summer period. The increase in the occurrence of fires is already a threat not only to the vegetation cover, but also to the residential structures that are built in the rural areas, which are increasingly vulnerable. For this reason, it is very plausible that the changes caused in the natural ecosystems by the changes of the climate affect this set of benefits usually associated with the forestry activity.

As seen in previous sections, burning, or simply the "use of fire", are the main causes of the occurrence of rural fires in Portugal, and its control and, if necessary, prohibition is urgently needed. Although it is an ancestral practice, with the worsening of climatic conditions, especially during the summer period, but which, as previously seen, now also extended to spring and autumn, the risk associated with this practice has grown exponentially. Most likely, the need to extend the so-called "rural fires season" will arise in the short term, where all means of combat are on alert so that they can react in a timely manner to any emergency.

Almost all climate models anticipate a decrease in the amount of precipitation in various parts of the globe, but they emphasize in particular the effects on the Mediterranean climate regions. The parallel effect of temperature increasing and reduction of precipitation may lead to a significant decrease in the amount of soil moisture.

According to the information provided in the previous sections, there is already a tendency for climatic anomalies related to the increase of average air temperature in Portugal, associated with the occurrence of anomalies related to the amount of precipitation in several months of the year. That is, the trend indicates a strong probability of occurrence of periods of temperature rise associated with lower levels of precipitation.

This lack can make trees more fragile from insect pest attacks and diseases, but also from increasing the likelihood of rural fires. The frequency and intensity of these occurrences will determine the type and rate of conversion of soil cover to a new state, for example the replacement of a forest composed of native species, by another one composed of invasive species. In Portugal, infestations of extensive forest areas by species of the genus *Acacia* begin to be very frequent, but there are others, such as *Hakea*, that begin to occupy very significant areas and are no longer limited to occupying space along the circulation ways.

However, as a consequence of climate changes, forests can undergo more rapid changes; for example, unless a significant increase in precipitation occurs, the severity of rural fires may increase. For this reason, it is urgent to create a model of forest management that takes into account the phenomenon of climate changes and all associated variables, and not to forget that forests are a natural resource that can should be profitable, with a view to sustainability for the future.

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CHAPTER 2 – Framework

Chapter Index

climate

MDPI

Review

Forest Contribution to Climate Change Mitigation: Management Oriented to Carbon Capture and Storage

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Abstract: Today, climate change is assumed by many researchers and scholars as a certainty and is presented as the biggest challenge humanity has ever faced. It is commonly accepted that anthropogenic greenhouse gas emissions are the main cause that is accelerating the process. Therefore, it is urgent to find solutions to mitigate climate change, mainly because the intense effects have already been felt, in many cases in the form of the occurrence of extremely violent weather events. Forests are undoubtedly one of the most effective and easiest ways to provide the function of carbon sinks. However, it is essential and convenient to analyze the permanence time of this carbon in forests, because this permanence time depends directly on the forest management model used. This article aims to analyze forest management models from the perspective of carbon residence time in temperate forests, dividing the models into three types, namely carbon conservation models, carbon storage models, and carbon substitution models, according to their ability to contribute to functioning as carbon sinks, thereby contributing to the mitigation of climate change.

Keywords: forest management; climate change; carbon sinks; carbon cycle

1. Introduction

Mankind is currently facing one of the greatest challenges it has ever faced, and must be prepared to efficiently solve and adapt to the problem, because even if organized in an integrated and global manner, the solution will not be immediate [1–3]. Climate change is a reality which is assumed almost unanimously by the scientific community, but also by the majority of the general population who, even without understanding the technical and scientific components associated with the phenomena, feel the implications and changes in their daily lives [4–6]. An example of these situations is the occurrence of extreme weather phenomena, in particular, concerning forest environments, which have a direct consequence by increasing the occurrence of rural fires and changing environmental conditions that lead to the proliferation of exotic forest species that could present an invasive behavior due to a faster adaptation to the new climatic parameters [7–10].

Assuming that an increasing concentration of CO_2 in the atmosphere is the main cause of climate change acceleration, without discussing the origin of this CO_2 (Figure 1), it seems clear that the first steps to mitigate the changes are any that can somehow reduce this CO_2 concentration [11–14]. However, increasing concentration of CO_2 in the atmosphere can be attributed to anthropic activity in the increments of 7.8 ± 0.8 PgC yr^{-1} and 1.1 ± 0.8 PgC yr^{-1}, respectively, associated with fossil fuel use and land use change [15]. In other words, it is a set of all the measures that are implemented to have

CO_2 sequestered from the atmosphere (Figure 2), but at the same time stored for as long as possible, somewhat delaying the natural carbon cycle [16–18].

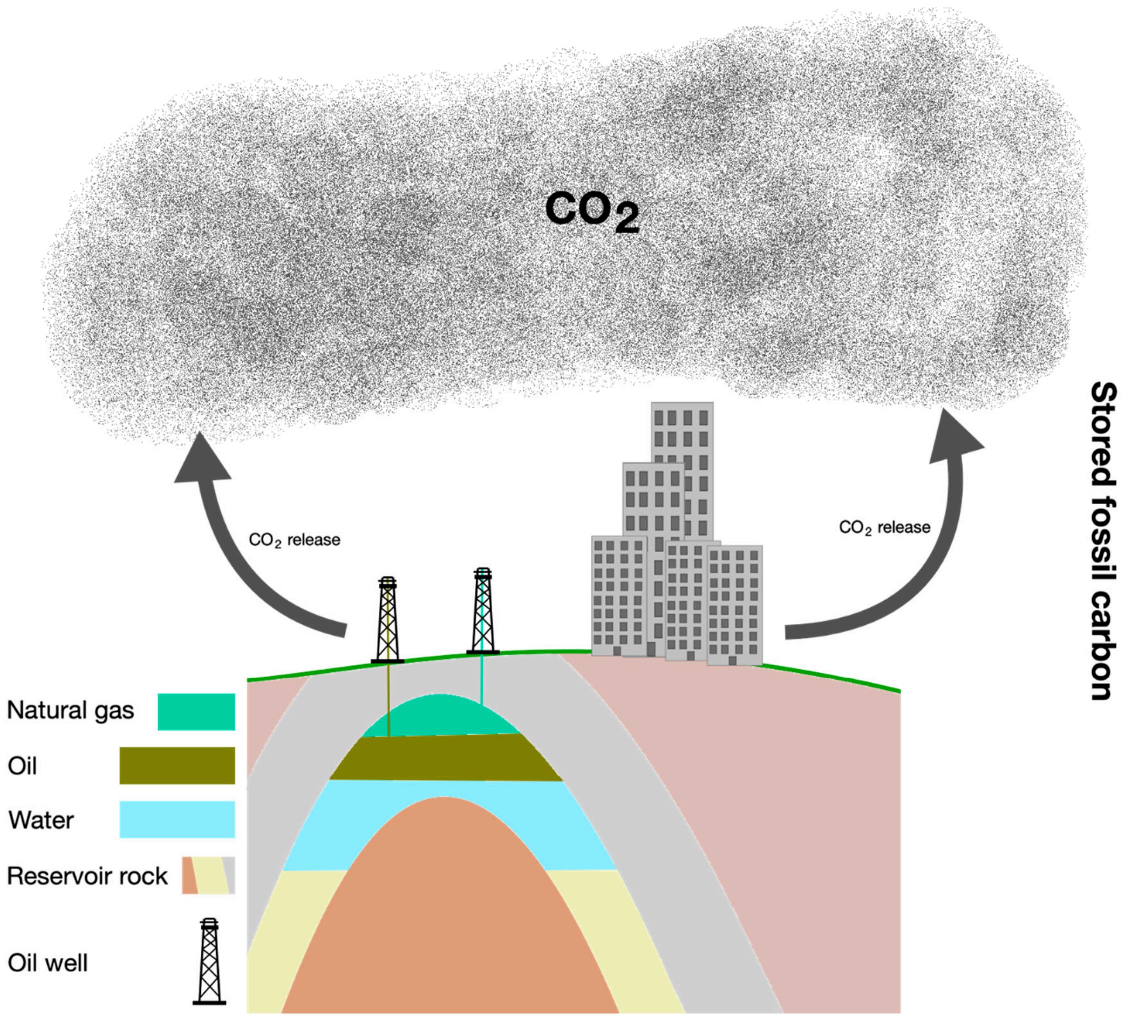

Figure 1. The release of carbon sequestered and stored in the distant past is most likely the leading cause of accelerating climate change. The increasing use of fossil fuels since the period of the industrial revolution is, on the one hand, the basis of societal development as it has made available accessible energy sources, but, on the other hand, it has contributed greatly to pollution and to the increased concentration of CO_2 in the atmosphere.

A process, activity, or tool that contributes to CO_2 removal from the atmosphere and to storage for a certain period of time is known as a carbon sink. This storage occurs mainly in oceans, soils, and forests, where organisms capture carbon and release oxygen into the atmosphere [19,20]. The balance between CO_2 captured by forests through photosynthesis is 14.1 PgC yr^{-1} and the CO_2 released through respiration and forest fires is 11.6 PgC yr^{-1}, representing a positive balance of capture and storage [15]. Carbon sinks work like a drain, and unlike sources that emit more carbon than they absorb, they absorb more carbon than they emit. Because it is a natural and environmentally friendly process, human actions have been negatively interfering [21], because burning of fossil fuels, as well as different land uses associated with deforestation and burning, are the main causes of the increase in CO_2 levels in the atmosphere. This destruction consequently makes storage more difficult [22].

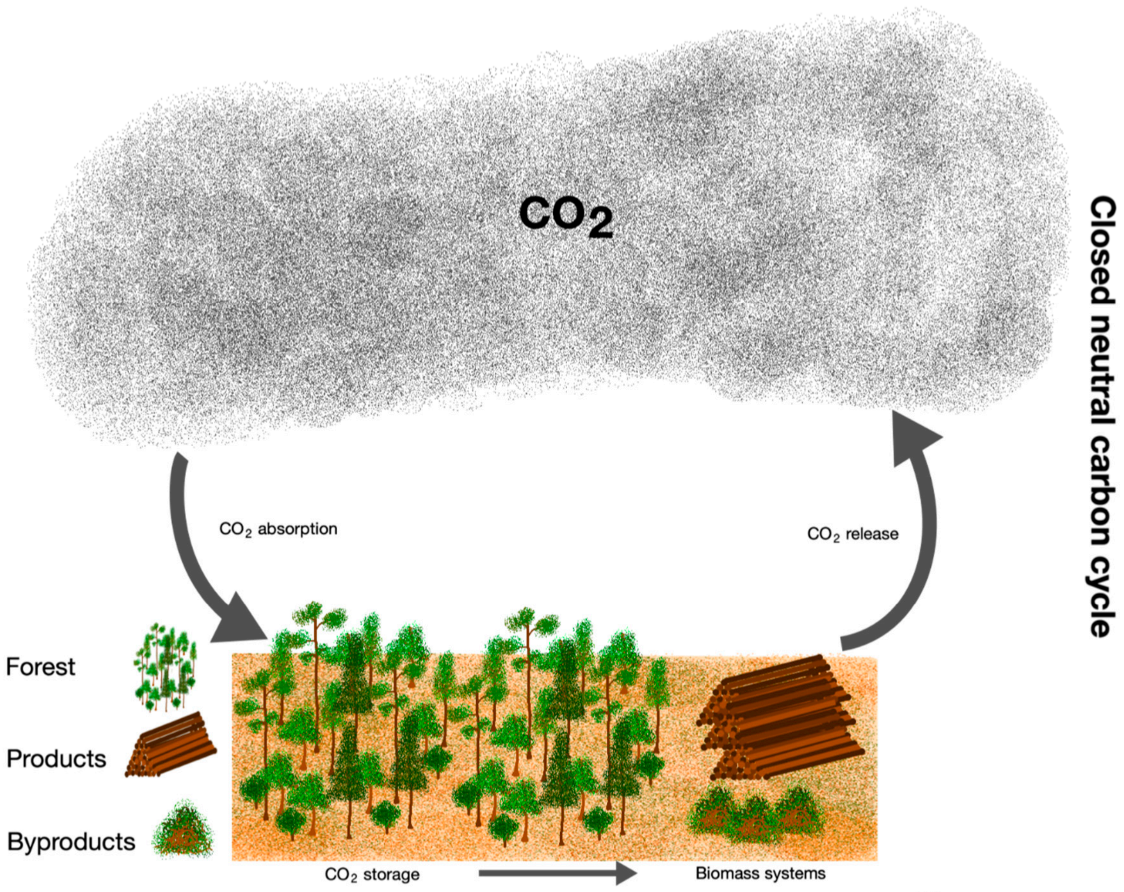

Figure 2. Forests are able to create their own carbon cycle, as trees and plants in general, take CO_2 out of the atmosphere and use it to create their own organic matter, along with water and sun energy, through photosynthesis. It is this process that allows the use of biomass energy to be considered carbon neutral, as it is considered that the carbon emitted is only that which the plant has absorbed and stored during its lifetime.

In this perspective, forests present themselves as a potential solution, as they can effectively contribute to CO_2 capture and sequestration over different time periods [23]. These periods are greater the longer the longevity of the forest species used, but also totally dependent on the intended purpose for the forest [24], that is, whether short rotation periods are used, as in the case of energy crops, or long rotation periods are used, as in the case of forests intended for the production of timber for construction or shipbuilding [25,26].

In 1997, the Kyoto Protocol suggested that the absorption of carbon dioxide by trees and soil is as valid as reducing CO_2 emissions from burning fossil fuels [19]. As a result, trees, other plants, and soil were given great importance as temporary carbon sinks emitted into the atmosphere by burning fossil fuels [27]. However, there is a movement against these carbon sinks because their effect cannot be accurately measured, especially in forests as trees absorb different amounts of carbon and the carbon movement in soils is unknown [28,29].

In addition, there is a problem of interests. Land used for carbon sink projects requires legal agreements that prevent land use for many years [30]. In this way land is used to generate emission rights so that the most polluting countries and industries continue to pollute while communities are unable to meet their needs [31,32].

From this point of view, projects involving reforestation and intensive planting of new forests have been emerging all over the world as they are presented as simple measures to implement [20,33,34]. Examples are the reforestation megaprojects being carried out in Africa or India [35–39]. For example, the green wall that is being erected in Africa, made of trees, to prevent the advance of the Sahara Desert. It is the 15 km wide and 7775 km long "Great Green Wall" across the African continent from Mauritania to Djibouti, with the aim of halting the advancement of the desert, improving the management of natural resources, and fighting poverty [40].

However, many other projects, perhaps less well-publicized, are also being implemented in several other countries, where they are also expected to contribute to climate change mitigation [41–43]. For example, the Cape Verdean government and FAO signed in 2017, a five million euro agreement for the European funding of the project entitled "Strengthening the Capacities and Resilience of the Forest Sector in Cape Verde". The project is to be implemented and financed by FAO with 133,000 euros, and carried out on the islands of Boa Vista, Fogo, and Santiago. The main objective is to increase resilience and strengthen the country's adaptive capacity in view of the additional risks caused by climate change, such as desertification and land degradation [44].

Capture and sequestration of atmospheric CO_2 by forests also present differences, because depending on the type of forest development implemented, the results obtained concerning carbon quantity and permanence time vary, and can lead to the achievement of different objectives [45,46].

The main objective of this review article is to analyze different management models applied to temperate forests, defined by their ability to capture and store carbon, but most importantly, for how long this carbon can be stored. Here, the models that are analyzed generically refer to the possibilities of land occupation with forest aptitude, but also are extensible to soils with other occupations, namely old agricultural soils, bushlands, and pastures. In this way, the potential contribution of forests to climate change mitigation is also analyzed.

2. The Global Carbon Balance

Although weather has changed throughout the history of the earth, in all time scales, it is clear that the current changes have some distinct aspects. For example, currently, the observed concentration of carbon dioxide in the atmosphere far exceeds the natural range of the last 650,000 years, reaching a record 415 ppm, an increase of about 100 ppm from the period prior to the industrial revolution [47]. Another distinct aspect of current climate change is its origin, unlike in the past, where climate change has resulted from natural phenomena, while most current climate change, particularly in the last 50 years, is attributed to human activities [48].

The main evidence of this current climate change is global warming, which has been detected in rising global average air and ocean temperatures, widespread melting of snow and ice, and rising sea levels, and which can no longer be denied [49,50]. Currently, the average global surface temperatures are at their highest as compared with at least five centuries. The global average surface temperature has increased by about 0.74 °C over the last hundred years. If this is no significant action concerning this warming, a very unusual climate is expected during this century which could present, for example, an average increase in global temperature from 2 °C to 5.8 °C, as reported in 2007, in the Fourth Report of the Intergovernmental Panel on Climate Change (IPCC) [51,52].

The concentration of atmospheric CO_2 has been measured directly and systematically in Mauna Loa (Hawaii, USA) since 1957 [53,54]. For periods prior to this date, this concentration can be calculated by analyzing the atmospheric composition of bubbles of trapped air in the ice of the poles [55–57], taking into account the fact that each bubble is composed of air of different ages and that the deepest ice retains older information (due to the progressive accumulation of ice) [58]. In recent years, a new set of satellites has been launched aimed at quantifying CO_2 in the atmospheric column, GOSAT and OCO-2, allowing global and continuous monitoring of flows and concentrations of CO_2 with moderate spatial resolution [59–62].

The Global Carbon Project (GCP), implemented in 2001, is a project that periodically documents the evolution of anthropogenic CO_2 emissions, as well as CO_2 flows in oceanic and terrestrial reservoirs [63]. GCP analyses are limited to the final decades of the twentieth century, for which data obtained through direct observations are available. For earlier periods, the only existing records come from air trapped in the polar ice caps [64]. However, the calculation of fluxes present in the terrestrial carbon balance for these periods presents great uncertainty [65].

CO_2 emissions from fossil fuel combustion and industry, fossil fuel emissions (FFE), are usually based on energy statistics and cement production data from different organizations, e.g., Carbon Dioxide Information Analysis Center (CDIAC), International Energy Agency (IEA), and United States Department of Energy (DoE), with CDIAC estimates being the only ones providing data since 1751 [66–68]. Emissions from land use and land cover change (LULCC) have been dominated by deforestation in recent decades [69]. They are generally based on statistical or satellite data (where available) of land use and land cover changes and are calculated using various types of models, these data currently being combined with information on fires (related to human intervention), usually from satellites [70,71].

Observations of ocean CO_2 fluxes (SOCEAN) have been made from the 1970s onwards by measuring the surface CO_2 pressure (pCO_2) [72–74]. However, these observations correspond to point measurements in the oceans, which means that global sequestration is not necessarily known. It is for this reason that annual anomalies and trends in the global ocean sink are usually estimated using ocean models (as in the GCP, for example) [75].

With respect to CO_2 fluxes in terrestrial ecosystems, the only direct measurements available are point data of turbulent vertical gas flows in the atmosphere (eddy covariance flux), and these data are available for long periods and homogeneous topography locations [76,77]. These measurements have been in existence for a few decades (since the 1990s systematically) and are organized in continental and global networks such as FLUXNET, which enables global and regional assessment of CO_2 exchange [78–80]. FLUXNET is a network of meteorological sensors measuring atmospheric state variables, such as temperature, humidity, wind speed, rainfall, and atmospheric carbon dioxide, on a continuous basis, and serves to predict weather, climate, and the cycling of carbon and water [81].

3. Carbon Flows in Terrestrial Ecosystems

Disruptions in the global carbon cycle are framed within a broader context as the "global environmental exchange", which in many ways ameliorates the functioning of the planet and includes various closely related phenomena and processes [82]. A global change is defined by the types of phenomena involved which include (a) One that alters the fluid layers of the Earth systems (the atmosphere or the ocean), and therefore is experienced on a planetary scale and (b) one that occurs in discrete but widely distributed places that constitute a global exchange [82–84]. Examples of the first phenomena include changes in the composition of the atmosphere (e.g., increases in the concentration of carbon dioxide and methane), climate change, the destruction of the ozone layer in the stratosphere, and an increase of ultraviolet radiation. Examples of the second type of phenomena include loss of biodiversity, exchanges in its use (e.g., the destruction of forests for agricultural use), changes in atmospheric chemistry (e.g., the acidic cloud and the increase of ozone concentration in the troposphere), and biological invasions [85].

The common denominator of all the components of the global environmental exchange is human activity, which has acquired enormous proportions in relation to the energy and material flows at the global level [86]. The disruptions in the global carbon cycle have severe repercussions on the climate of the planet due to the properties of CO_2 and methane as greenhouse gases, such as a major concentration in the atmospheric atmosphere and the highest global average temperature of the planet [87].

To understand the factors that influence LULCC, one must consider the different biogeophysical, biogeochemical, and ecological processes that occur at different time scales and affect carbon flows in terrestrial ecosystems [88]. At short time scales, ecosystems exchange energy, water, and other chemical compounds (Figure 3), and these exchanges are regulated by physical and ecological processes on a daily basis or on a seasonal basis [89,90]. Energy and water exchanges are mostly influenced by vegetation or soil characteristics, such as albedo, which regulates the amounts of solar energy absorbed and reflected by the earth's surface, or soil water availability, which regulates the hydrological cycle and latent heat fluxes [91].

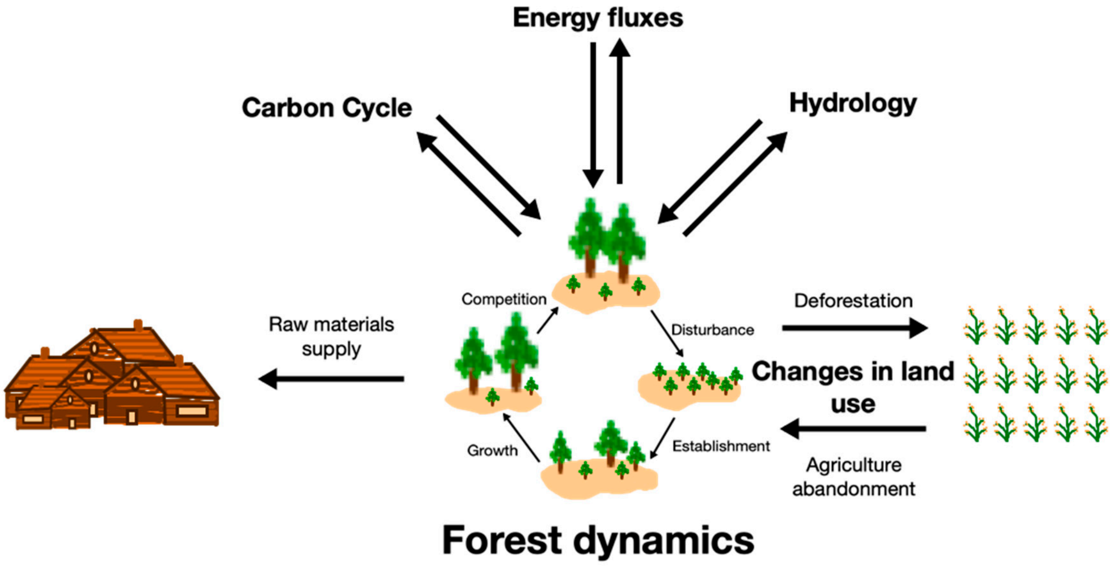

Figure 3. Schematic representation of the main biophysical and biogeochemical processes in terrestrial ecosystems (adapted from [89]).

General mechanisms operating jointly are considered to exist, but on different scales of time. In the broad range (hundreds of millions of years), the carbonate-silicate geochemical cycle operates as a concentration regulator [92]. In this cycle, atmospheric CO_2 dissolves in rainwater and forms carbonic acid that reacts with the minerals exposed on the earth's surface, generating what is known as weathering of the rock [93]. The rivers surround the products that are discarded by the ocean. In the ocean, calcium carbonate is formed. This is deposited in the marine sediments through the process of subduction between the low crust of the Tierra. In this process, elements are reincorporated into the primary minerals of the rocks and the carbon returns to the atmosphere as CO_2 by the volcanic and hydrothermal emissions. This geochemical cycle has helped to maintain atmospheric CO_2 concentration by a 1% decrease over the last 100 million years. However, annual carbon flows are relatively small [92,94].

Radiative and hydrological processes, therefore, play a fundamental role in the functioning of terrestrial ecosystems (through variables such as temperature, precipitation, evapotranspiration, and soil water profile) [95]. Momentary changes are associated with wind-borne energy, whose behavior influences soil and plant evapotranspiration [96]. CO_2 flows are mostly related to photosynthesis, respiration, and decomposition of organic matter, and are largely conditioned by other physical processes. Examples of factors influencing the various processes mentioned above are the seasonal variability of solar radiation, local hydrology, nutrient absorption, and mineralization, or vegetation phenology and resource allocation [97].

The ability of terrestrial ecosystems to function as carbon sinks depends, to an important extent, on the "fertilization effect" due to the increase in the concentration of carbon dioxide in the atmosphere and the deposition of atmospheric nitrogen, which is emitted in excess for various human activities [98]. Fertilization by CO_2 is possible, and its current atmospheric concentration limits the productive capacity of plants [99]. There is evidence that the effect of fertilization increases the growth of plants under natural conditions, however not to the extent that physiological studies of individual plants and controlled conditions suggest [100].

As schematized in Figure 3, over a year, ecological processes affect the structure and composition of ecosystems, which in turn control short-term functioning, such as competition between different vegetation types, nutrient deposition, and regime disorders (e.g., fires, droughts, and pests) [101]. Human activities also interfere with the structure and functioning of terrestrial ecosystems through LULCC, soil and forest management, or the addition of nutrients to ecosystems [102].

As represented in the figure, ecosystems are dynamic and their composition and structure changes over time. There are periodic disturbances such as fires, hurricanes, droughts, floods, and pests that substantially change grasslands, forests, estuaries, mangroves, and other communities. These events are known as disturbance regimes and change from region to region depending on weather conditions. Currently, the main disturbance regime is human activities. Wood harvesting from forests, roving crop systems, and other activities transform ecosystems into successive states.

Carbon is found in the atmosphere, the biosphere, the oceans and the sediments [103]. Plants use CO_2 from the atmosphere and convert it into carbohydrates and in this way, much is stored in forests and soil. In the sea, many organisms use carbon to form their external skeletons and their shells [104]. Carbon returns to the atmosphere through the respiration of organisms, organic decomposition, combustion, and volcanic eruptions [74]. The other chemical elements have similar cycles [105].

Water is the most abundant molecule on the surface of the planet Earth. It is the only molecule that can be found naturally in a solid, liquid, and gaseous state and is essential to all life on Earth [53]. The properties of water provide a perfect medium for biological reactions that occur within cells, from the ability to store energy through photosynthesis, to energy consumption through respiration [106]. The water that evaporates from the oceans with the energy of the sun is transported by the circulation of winds around the planet [107]. When wind is rising, following the contours of the mountains, the wind cools and transforms into rain providing moisture to forests, jungles, grasslands, and thickets and suppling streams, rivers, lakes, groundwater, and finally returns to the sea [108]. In this long way, water is absorbed by plants and consumed by animals that require it since it constitutes between 55% and 80% of living beings [109].

Living things require energy to perform their basic growth, reproduction, and survival activities. Plants are the primary producers that transform the sun's energy into chemical energy through photosynthesis. First the chlorophyll molecule absorbs the energy of light and divides the water molecules into hydrogen and oxygen [110]. As a second step, carbon dioxide is transformed into carbohydrates (sugars), that is, into larger molecules of carbon, hydrogen, and oxygen [111]. Herbivores, as primary consumers, feed on plants and obtain nutrients and energy from them, which in turn are passed to carnivores and from these to decomposers [71]. The flow of energy through living beings is known as the trophic chain or food chain and each of the levels through which it passes, is known as a trophic level [59].

4. Forest Management based on Carbon Capture and Sequestration Capacity

4.1. Carbon Conservation Model

As noted above, the process of carbon capture and sequestration involves removing carbon dioxide from the atmosphere. This process occurs mainly in oceans, forests, and other places where organisms, through photosynthesis, capture carbon and release oxygen into the atmosphere. It is the capture and safe storage of carbon dioxide (CO_2) that prevents its emission and permanence in the atmosphere [112,113].

Figure 4 is a schematic representation of this type of model, which shows the major interactions that contribute to a forest management trend in which carbon concentration is conserved in the forest [114]. Theoretically, this model does not contribute to the reduction of atmospheric carbon, but also does not contribute to increasing its amount [115]. Concerning the carbon content, this model is considered neutral [116]. However, this claim presents some controversy for several authors [117–124], in particular, whether the primary mitigation value of forests is in instantaneous and short-term flux rates and product substitution or stock longevity [120,122,125–129].

Examples of measures projected to increase the conservation of a larger carbon content include increasing coppice rotation periods, avoiding damage to trees during forestry operations, reducing logging residues by applying soil conservation techniques, and using wood in a more carbon efficient way [130].

An example of this forest management model is found in the *Eucalyptus spp.* planted forests for the pulp and paper industry supply [131–133], but other examples are found in *Acacia* spp. or *Salix* spp. plantations for energy production, where the species used have rotation periods shorter than 15 years, depending mainly on the location and on the species characteristics [132,134]. This type of forest with shorter rotation periods conserves carbon content. In reality, this system only allows the carbon returned by industry to the cycle to be captured and stored, and does not allow a positive balance towards carbon sequestration for long periods [135].

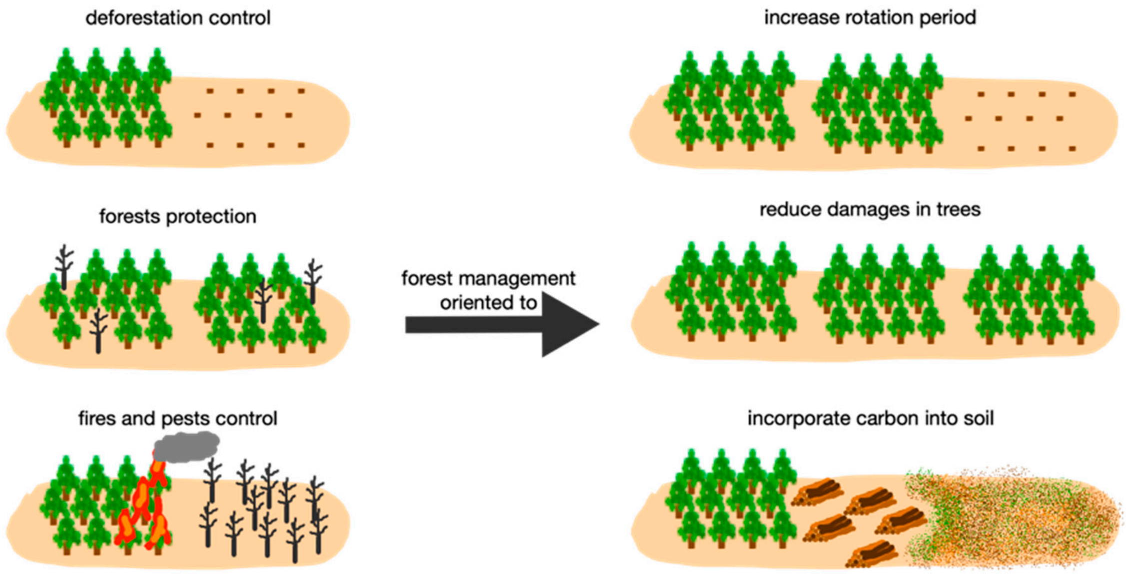

Figure 4. Forest management model for carbon conservation (adapted from [136]).

4.2. Carbon Storage Model

Figure 5 shows a schematic representation of the forest management model for carbon storage. The objective of this model is to increase the amount of carbon in the forest vegetation and soil, increasing the surface or carbon content of biomass in natural and planted forests by increasing storage in durable wood materials [137].

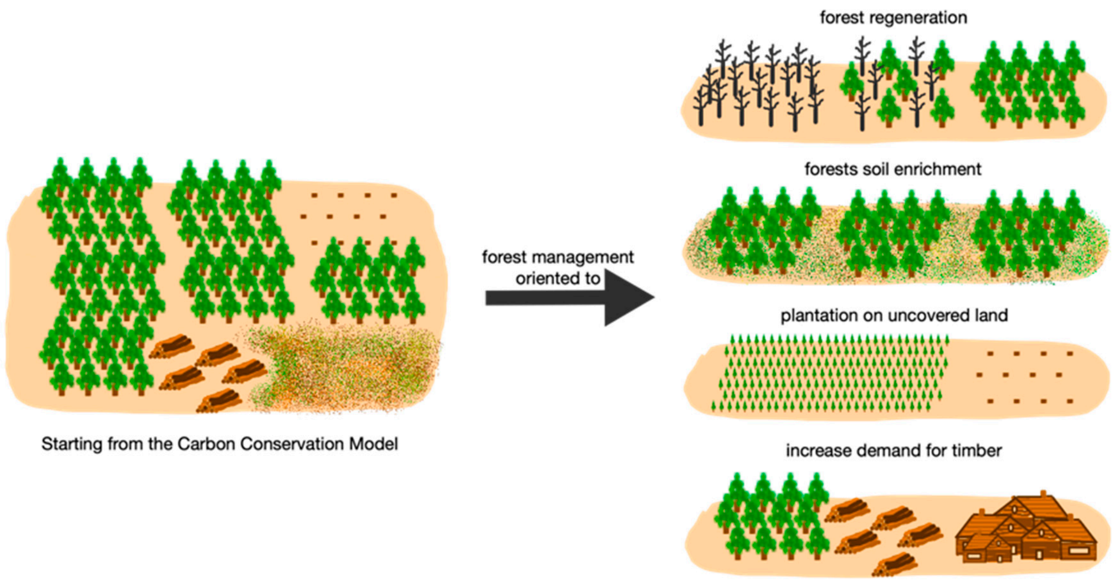

Figure 5. Forest management model for carbon storage (adapted from [136]).

To increase carbon storage in vegetation and soil, it is necessary to protect secondary forests and other degraded forest areas, those which have carbon content values below the maximum possible in both plants and soil, by carrying out regeneration and soil enrichment [138].

Reforestation of uncovered land together with the promotion of natural or artificial regeneration of secondary forests, and also increasing forest cover on agricultural land or pastures, are measures that contribute to increasing the amount of sequestered carbon [139].

In the case of timber products, carbon stocks can increase due to a higher demand for timber products, which is occurring at a faster rate than the rate at which wood deteriorates and due to the extension of the durability of timber products [140]. An example of this model of forest management can be found in the planted forests of *Pinus spp*., the most common species being *Pinus pinaster*, *Pinus elliottii*, or the *Pinus caribaea* var. *hondurensis*, used for the supply of resin gum for the chemical industry [141], but others can be found as well, such as, for example, *Hevea brasiliensis*, the rubber tree.

Forests with longer rotation periods of 15 to 25 years, where the replacement cycle of trees is longer that one used for energy or the pulp and paper industry, capture and sequester carbon fixation over longer periods [142].

4.3. Carbon Substitution Model

The main objective of this management model, as shown in Figure 6, is to increase the amount of carbon transferred from forest biomass to other products, usually derived directly or indirectly from fossil fuels, such as biofuels or building materials, instead of using fossil fuel-derived energy or cement industry-derived products [143]. This perspective presupposes the extension of the use of forests to supply raw materials and fuels. This can be achieved by the establishment of new forests or by increasing the growth rates of already existing forests [144]. However, the fact that wood products also create emissions should be taken into account, in particular the production of biofuels must be deeply analyzed once it contributes mostly carbon storage problems related with deforestation for land use [145].

This type of management model, i.e., forests where energy crops are settled on land without any sort of cover or with non-arboreous cover, can generate an increment in the total amount of carbon captured and sequestered in that area. Furthermore, biomass used as fuel replaces an equivalent amount of fuel with fossil origin, creating an effective carbon uptake rate in unburnt fossil fuels, known as offset emissions [146].

An example of this forest management model is when this management is implemented from the perspective of circular economy, where the byproducts resulting from forestry operations are converted into biomass-derived fuels, such as wood pellets or biochar and, then, used in substitution of fossil fuels [146]. This management model allows the captured and sequestered carbon to replace an equivalent amount of carbon of fossil origin [147], while maintaining the larger amount of carbon captured and stored for much longer periods, than in those models described previously [148].

Another form that can be considered inside this management model scheme are the *Quercus suber* plantations used in the supply of raw materials for the cork industry [141]. This type of forest with extremely long rotation periods, where the replacement cycle of trees is very long, allows the accumulated carbon to be captured and sequestered, allowing a positive balance towards carbon fixation over long periods [142,149,150], at the same time that it releases byproducts that can be included into a circular economy procedure [151]. In these forests, trees can present a rotation period much higher than 25 years, as is the case of the above mentioned *Quercus suber* for cork production, where the economic viability can be reached only after 25 years when the first cork is extraction, but the profit only arrives after the third cork extraction, 18 years after, maintaining this capacity cyclically each 9 years and during almost 200 years [152].

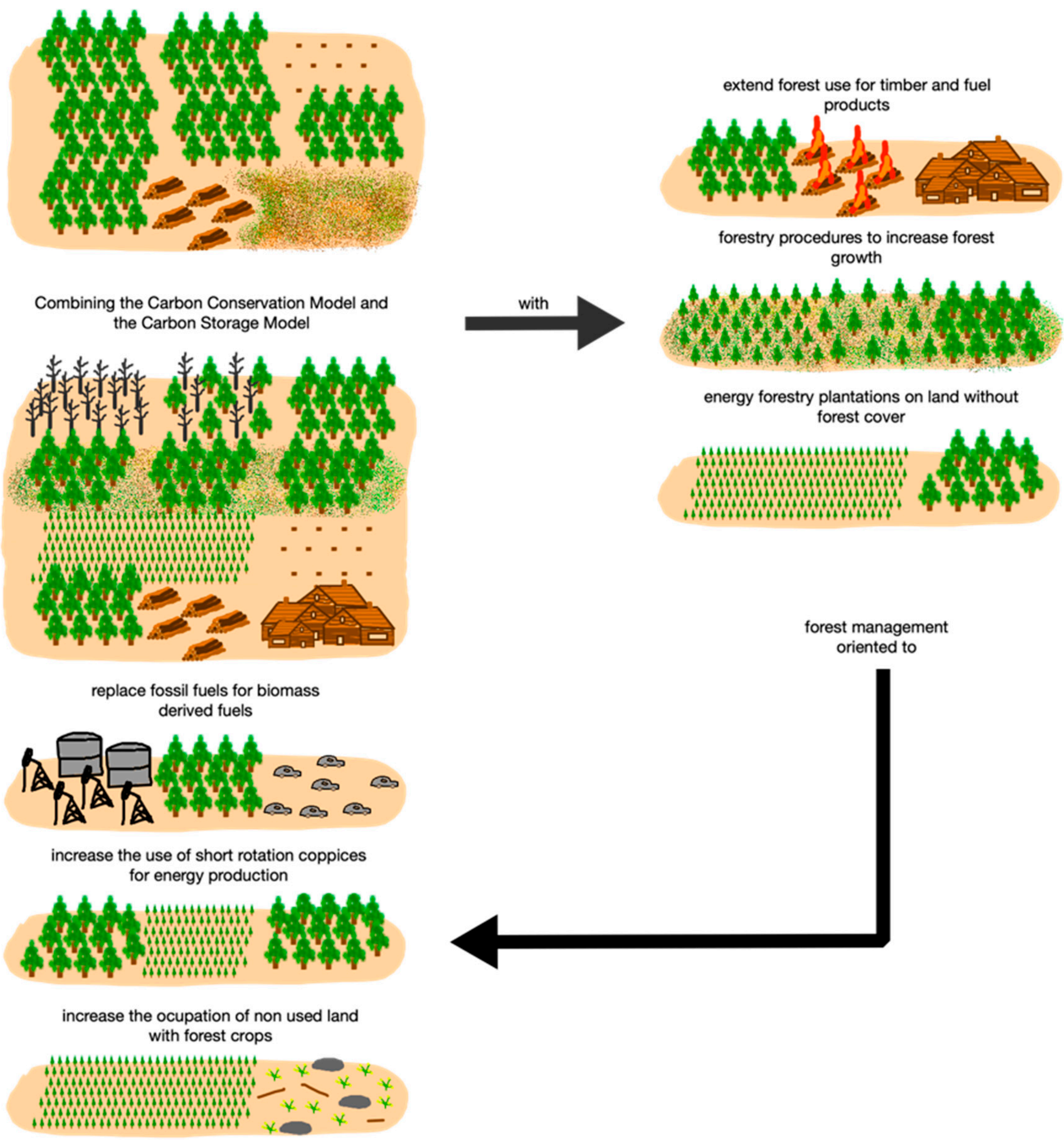

Figure 6. Forest management model for carbon substitution (adapted from [136]).

5. Discussion and Conclusions

It is commonly known that forests are a very important part of the carbon balance. A large part of the terrestrial carbon with organic origin is captured and sequestered in the biomass generated and in soil. As a main result, alterations in the CO_2 balance in forest ecosystems occur, which are due to changes in use or changes in the management model, with significant impacts on the concentration of atmospheric CO_2.

Forest management is defined as the use of forest resources through sustainable techniques, preserving species and ecosystems. In the case of industrial exploitation, this management can be done through productive rotation, in which the mature trees are cut, while the young ones grow to be cut in the future, while new seedlings are planted, in a continuous cycle of extraction and preservation.

The interactions between the forest management models described here are outlined in Figure 7. Each one of the models is analyzed from the perspective of the intensity with which different forms of management model can be applied, and the tasks leading to the fulfillment of the intended objectives. Forest management increases the chances of continuing to harness natural resources over the years and reduces the risk of deforestation and forest devastation.

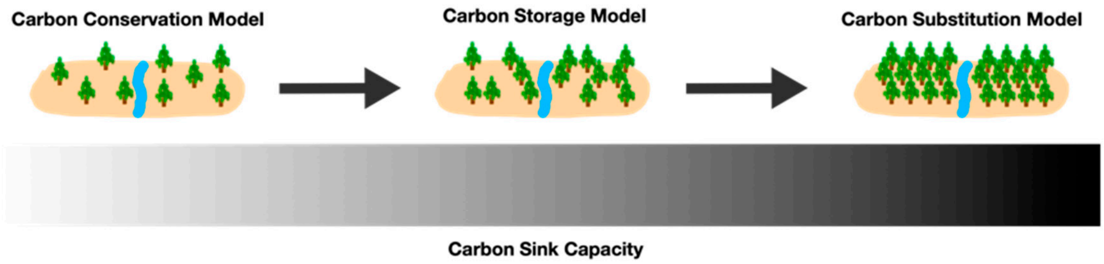

Figure 7. Models of forest management based on carbon flows.

The carbon conservation model is the most common, basic and simplistic model, and the one that normally occupies the largest forest area, even when there is no concrete objective of immediate raw material supply, but rather because forest owners have the short-term perception of earning income. Other models are more complex, including more variables and more mitigation measures used to significantly increase the carbon capture and sequestration rates, and finally, in the last model presented, mitigation measures are used for offsetting emissions [153].

These approaches include the production of raw materials, such as timber and fuels, and also environmental goods and services (Figure 8). Therefore, this must be understood as an opportunity to expand the vision of planning forests as a resource, considering in the planning the inclusion of environmental services for carbon capture, fixation, and storage, in other words, produce the service of a carbon sink that is used to finance the development of new forests.

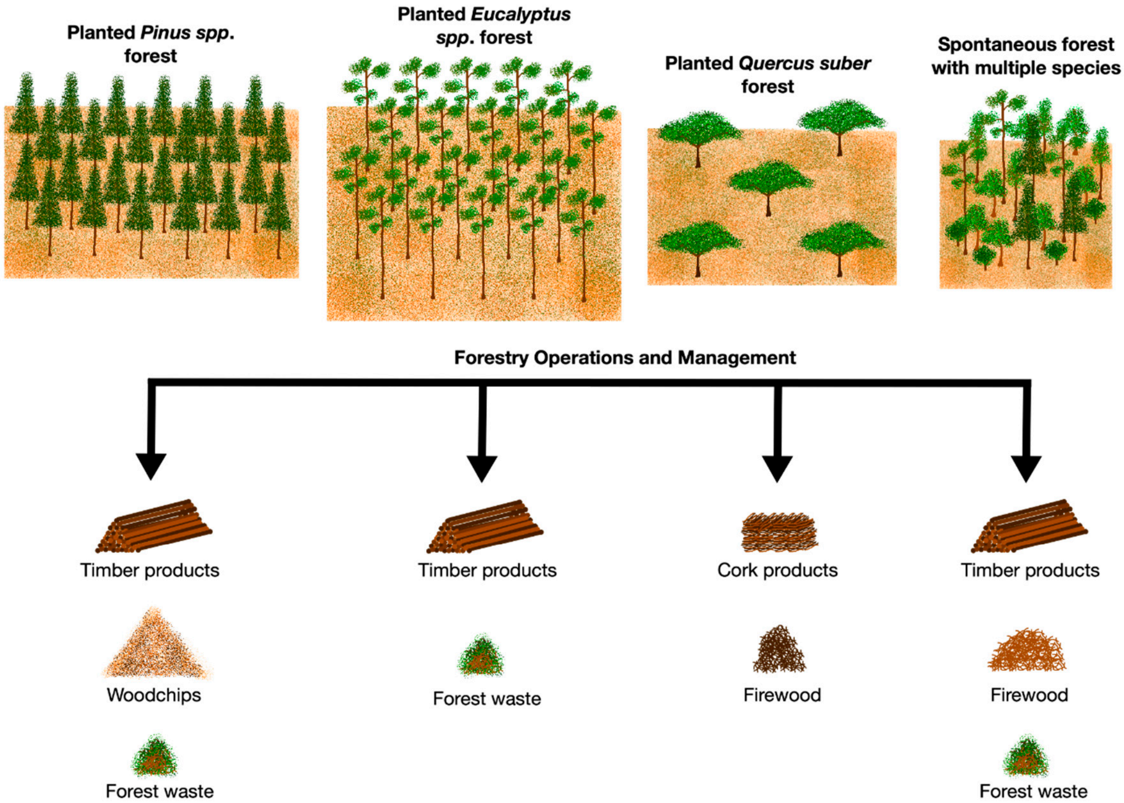

Figure 8. Different types of forest species also provide different types of products. However, in some cases, the products supplied are similar, varying only in quantity and quality. For this reason, the potential economic value varies with the choice made for afforestation.

Trees are generally species with longevity. The cycles of growth and basal metabolism of trees are processes that usually depend directly on climate conditions over time (Figure 9). This is mainly true with regards to temperature, precipitation, and solar radiation. Thus, any changes in these factors affect the growth rates of trees, and even the survival of the species, especially when these changes happen too fast, without giving time for forest species to adapt to new climate conditions.

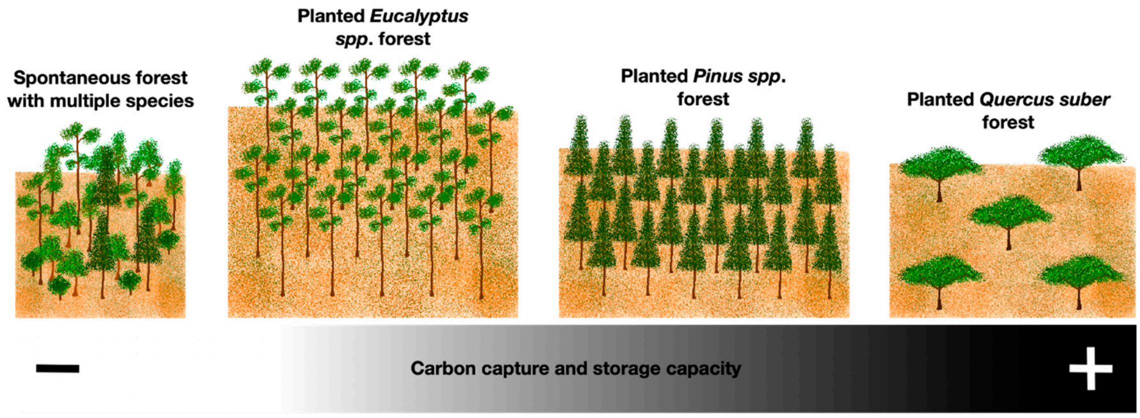

Figure 9. Carbon capture and storage capacity of different forest types.

Figure 10 schematically represents the different examples of forest management models associated with the capacity that each type of model can have in storing carbon over time. As can be seen from the graphs shown, this storage capacity is directly related to the rotation time used. Thus, it is considered that models that use short or medium rotation times, such as the rotation periods associated with *Eucalyptus* spp. or *Pinus* spp., have equivalent storage capacities. Planted forests of *Quercus* spp., or similar species, have a higher carbon storage capacity over the long term, as the rotation periods used can reach many tens, or even hundreds of years. Any of these forest management models have high potential economic returns given the quantity and quality of the products supplied.

It is also possible to relate the risk of fire with the use of these forest management models, as it is understood that the risk of fire decreases in direct proportion to the increment of management and operation activities, namely through cleaning, sanitary thinning, or from cutting down sick or defective trees. Thus, the risk of fire is higher in spontaneously growing forests, as the disorganized growth of several species increases the storage of high fuel loads due to the lack of management, because the poor quality of the products does not allow its monetization [154,155].

Forests, whether in an arctic, temperate, or tropical environment, play a major role in gas exchanges with the atmosphere, as they are the major flows of greenhouse gases. For the most important of all, CO_2, forests can be both source and sink. Thus, during the daytime, forests absorb large amounts of CO_2. This amount is greater than that released by breathing. Thus, forests play the role of CO_2 sinks. Intuitively, mature, old primary forests should absorb a similar amount of CO_2 to the forests that can release CO_2, thus, achieving a balance. Two hypotheses are suggested to explain this positive balance:

(1) CO_2 storage is the response of the forest to climate change and especially to the increase of CO_2 concentration in the atmosphere;
(2) The most important forests on the planet are not as mature and old as previously thought, and therefore are still be in a phase of regeneration after disturbances, which has left deep marks in their functioning.

However, if forests store CO_2, cutting more than their regeneration capacity (intensive deforestation for agriculture or mining) causes a significant decrease in CO_2 storage, and in response, forests become sources of greenhouse gases. When analyzing the balance in a large forest region, it is important to specify which area the balance corresponds to, as an undisturbed forest is an important CO_2 sink, but taken together when disturbed forests and destroyed forests are included, and burned, the forest can be a major source of CO_2 to the atmosphere.

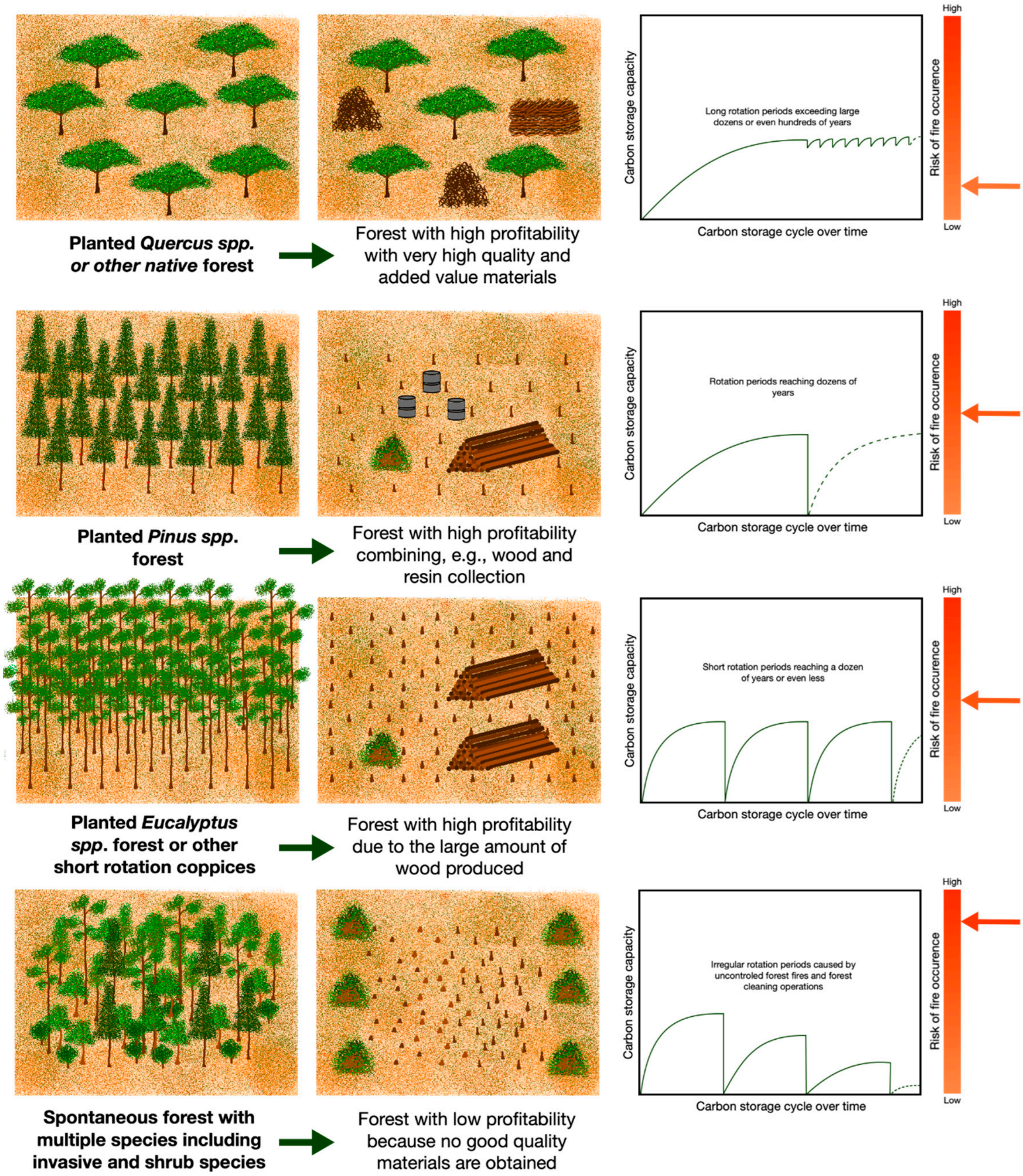

Figure 10. Relationships between different types of forest with potential economic performance, carbon storage capacity, and fire risk. Fire risk is a variable that has to be introduced, as this risk depends on the ability of temperate forests to keep carbon stored for longer periods, but also on the potential interest of forest owners to make a particular type of forest to the detriment of another.

Thus, it is necessary to discover the proper tools needed for native and planted forests in temperate regions to evolve with the new scenario of climate change. A critical phase that must be considered with particular attention is the phase of regeneration and implementation of forests, because young plants are deeply susceptible to and dependent on variations in radiation levels and water availability. This failure in the establishment could jeopardize equally the stability of native and new planted forests.

The idea embedded in the concept of carbon sinks is that tree plantations, through photosynthesis, could offset CO_2 emissions by absorbing CO_2. Many years ago, Larry Lohmann [156] warned that "the problem is how to calibrate a significant and reliable 'equivalence' between carbon permanently sequestered in fossil fuel deposits, transient CO_2 in the atmosphere, and carbon sequestered temporarily as result of any particular tree planting or national tree planting program. No one has a clue how to do that. Nor are they likely to have it someday".

It is important to consider that the magnitudes that are currently calculated for carbon sinks will not operate steadily in the future, as all key processes diminish. For example, carbon capture by young forests that grow in agricultural lands diminish as they mature. But it is expected that climate change effects on ecosystems will reduce the capacity of the sinks on a global scale. It is essential to take into account these limitations of the biological systems of the planet and to consider the global carbon balance in the future.

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CHAPTER 3 – Spread of Invasive Species

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The Impact of Rural Fires on the Development of Invasive Species: Analysis of a Case Study with *Acacia dealbata* Link. in Casal do Rei (Seia, Portugal)

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Abstract: Biological invasions can affect ecosystems in different ways. Invasive forest species, such as *Acacia dealbata* Link., affect forests' productivity, because they compete directly with native species for access to light and nutrients, contributing to the loss of biodiversity. In this study, an area occupied by *A. dealbata*, located in Casal do Rei (Seia, Portugal) was studied to evaluate the influence of fire in the dispersion of this species, analyzing the historical occurrence of rural fires in the region, as well as through the determination of its annual biomass production and comparing its growth with other species using satellite images. The research shows a competitive advantage for *A. dealbata*, even when compared to species, such as *Eucalyptus globulus* and *Pinus pinaster*, which practically disappeared from the location under study after a significant fire occurred in 2005, while *A. dealbata* continued to thrive.

Keywords: *Acacia dealbata*; rural fires; invasive species; annual biomass production

1. Introduction

The Mediterranean region has co-existed with fires since it was occupied by people. The region's climate determined the forests of the region and agricultural practices [1]. The concurrence of fires has shaped the ways of life of the people of the region. They have adapted to the seasonal climate, and frequent fires, and used those to their benefit [2]. Over time, this coexistence has become more complex. The frequency of fires has changed from an occasional to frequent occurrence [3]. In Portugal, the season at which fires occurs is defined and civil protection forces annually plan their mitigation efforts accordingly [4]. Fires are designated in different ways, depending on the type of area in which they may occur. The designation "forest fire" is often applied in a wrong way and is used when areas with other types of non-forest land use burn, such as are the shrubs and pastures areas. In this study, the designation "rural fire" is used referring to fires that occur in a rural environment, not distinguishing forest fires from those occurring in agriculture or shrubs and pastures areas.

The analysis of the data that are presented in the provisional report on rural fires of the Instituto para a Conservação da Natureza e da Floresta (ICNF) (a summary is shown in Figure 1) indicates that, in Portugal, rural fires are mainly caused by human activity.

Natural causes, such as lightning strikes, only accounted for 2% of the occurrences in 2020, while the average over the decade 2010 to 2019 was just 1%. The causes attributed to human activity, whether negligent or arson, represent most of the events analyzed, with 76% during the year 2020. This value is in line with the average over the referred decade, for which the value reached 72%. However, occurrences with arson origin have significant weight when analyzed individually, representing 37% of the events during 2020, a significant increase from the average for 2010 to 2019, i.e., 27% of the occurrences.

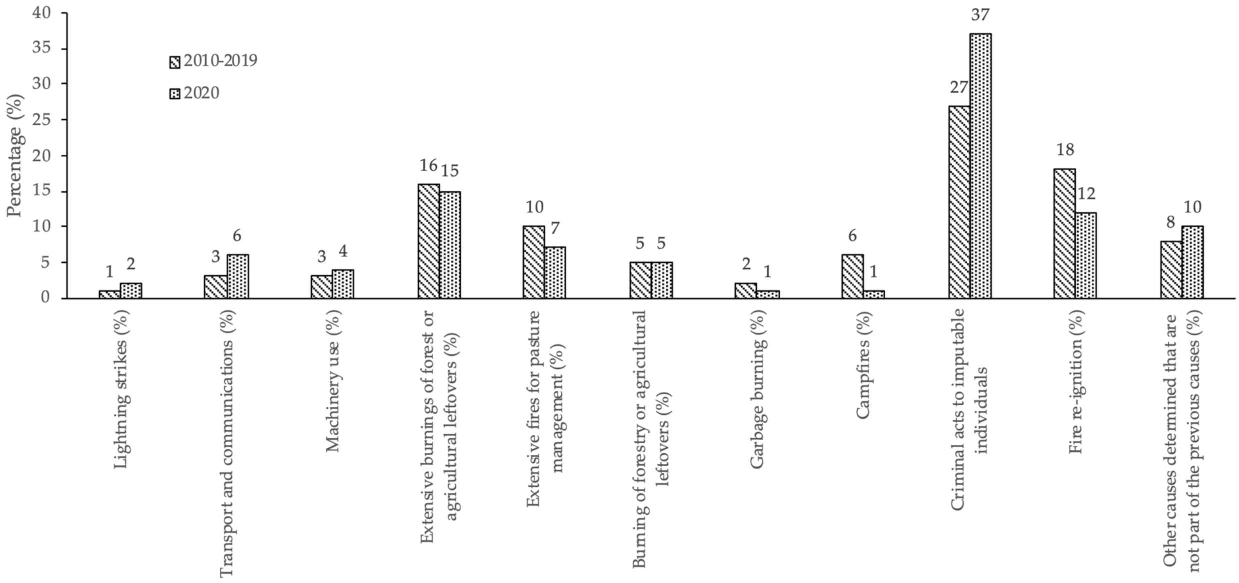

Figure 1. Frequent causes of rural fires in Portugal (data collected from http://www.icnf.pt/portal/florestas/dfci/relat/rel-if/2020, accessed on 12 January 2021).

The misuse of fire continues to be problematic. Such mainly negligent use causes a high percentage of rural fires and it is associated with practices, such as extensive burning for pasture management, the burning of waste materials resulting from forestry and agriculture, the burning of garbage, or holding bonfires for leisure activities, totalizing 29% of the occurrences in 2020. Despite this high percentage, there was a decrease when compared to the decade 2010–2019, which was 39%. The reduction may be associated with intensive public awareness activities, and restriction and control measures implemented after the fires occurred in 2017. During 2020, these measures were accentuated by the impact of the COVID-19 pandemic by reducing the economic and leisure activities of the population in a generalized way.

Contrasting with previous periods, during which fires were seen as a way of renewing agro–silvo–pastoral systems, serving to eliminate plagues, revitalizing meadows and pastures, and fertilizing soil through the deposition of ashes, rural fires are seen today as a difficult problem to manage. The occurrence cycles are shorter and are not long enough to allow the regeneration of the systems [5]. For example, when successive occurrences are recorded in a certain area with annual repetition cycles, the forest species that can settle and start to prosper will be only those adapted to post-fire conditions. These are usually invasive species coming from arid environments where fire contributes to their spreading. In Portugal, there are some species that proliferated in post-fire scenarios, where those of the genus *Acacia* stand out.

In Portugal, the spreading of species of the genus *Acacia* has been the subject of several studies, mainly contributing to the mitigation and control of their dispersion since there has been an increment of the occupied areas. *Acacia dealbata* Link. aroused significant interest due to its dispersion capacity in burnt environments since it is a pyrophyte species [6]. As shown in Figure 2, the increase in the area occupied by species of the genus *Acacia* occurred precisely when the rise in the number of rural fires started (in the mid-1990s), because of several circumstances, such as the abandonment of rural environment by the population searching better living conditions; the agricultural labor force transferred to the civil construction sector with the advent of public works made possible by European Union funds and by the forest reorganization to produce raw materials in a monoculture regime [6].

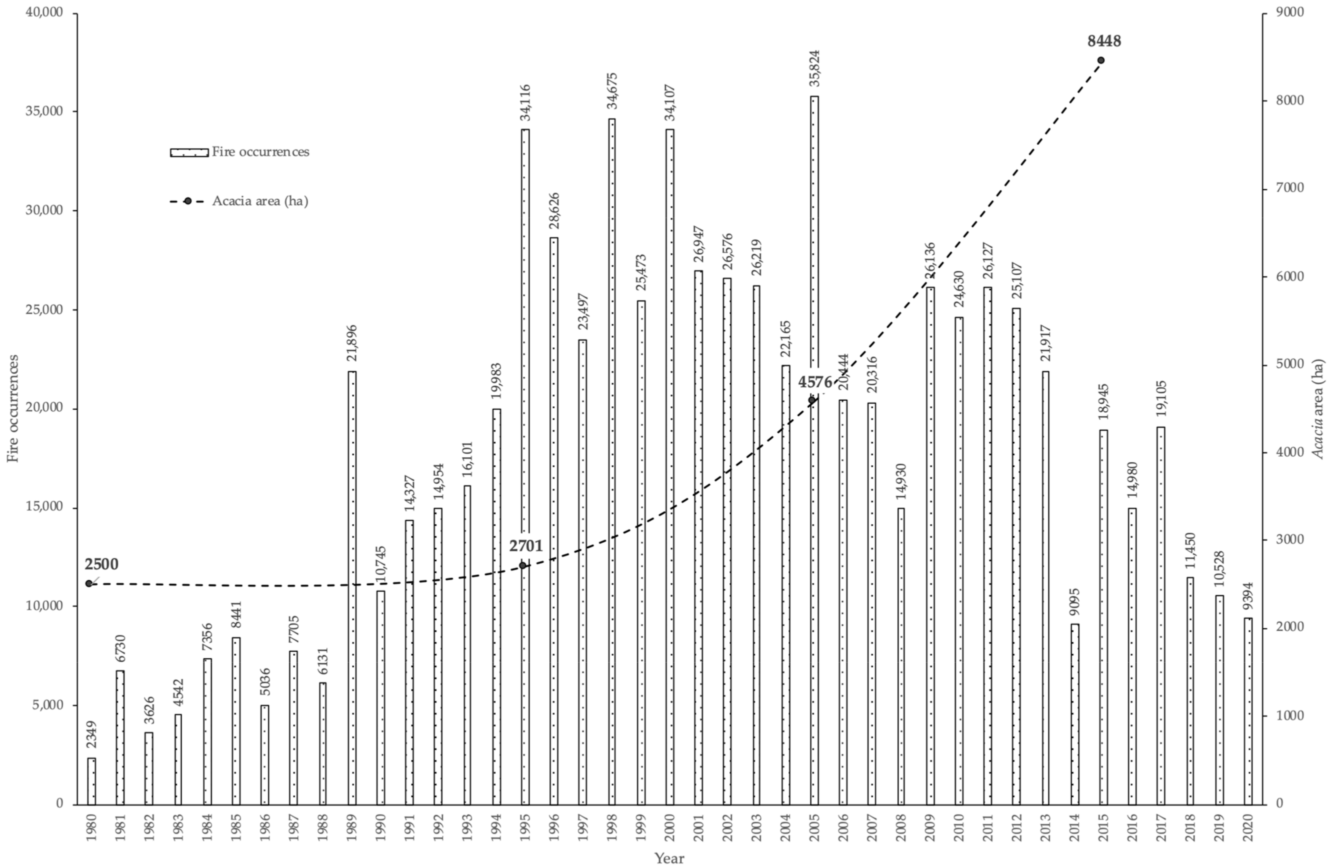

Figure 2. Evolution of the *A. dealbata* area (data collected from www.icnf.pt, accessed on 12 January 2021, and [7–9]).

The growth of the area has been a problem, especially after large fires, since *A. dealbata*, being pyrophyte, benefits from the destruction of the vegetation cover, allowing for its seeds, deposited in the soil for long periods, to benefit from direct exposure to sunlight. Because *A. dealbata* is heliophilous, it can develop much faster than other plants and, due to its capacity for allelopathy, can prevent or hinder the development of other species [10–12]. These plants can occupy the area and thrive with incredible speed to produce seeds, which are released in great abundance onto the soil [13]. As new rural fires have decreased, acacia stands are growing in the direct proportion to their capacity to reach maturity and produce seeds in between new events [14,15]. Thus, their capacity for territorial expansion depends directly on the number of seeds that each specimen can produce and its ability to disperse them around its location [16]. Afterwards, is only a matter of time to the occurrence of a new fire, which will unblock the access to sunlight activating the germination of the seeds [17,18].

Analyzing a case study in Casal do Rei (Seia, Portugal) is the purpose of this article, where the occurrence of rural fires during the last two decades led to a profound transformation of the forest, with the establishment of several *A. dealbata* stands that are prospering, contrary to what is happening with other species. In this article, the sequence of occurrences of rural fires in the region is characterized, and a comparative analysis of the growth cycles of the specimens from one of these stands is made to demonstrate how this species benefits in these new circumstances of climate change and most frequent post-fire scenarios.

2. Materials and Methods

2.1. Location of the Study Area

Casal do Rei is in the União de Freguesias de Vide e Cabeça, which is the result of the merge of two parishes in the municipality of Seia (Portugal). The parishes of Cabeça and Vide were unified in the administrative reform of the territory, which was approved by Law No. 56/2012 of 8 November and Law No. 11-A/2013 of 28 January. Figure 3 shows the location of the area under study and its regional and national framework. The site is located on the opposite slope to the villages of Cabeça and Casal do Rei (Figure 3).

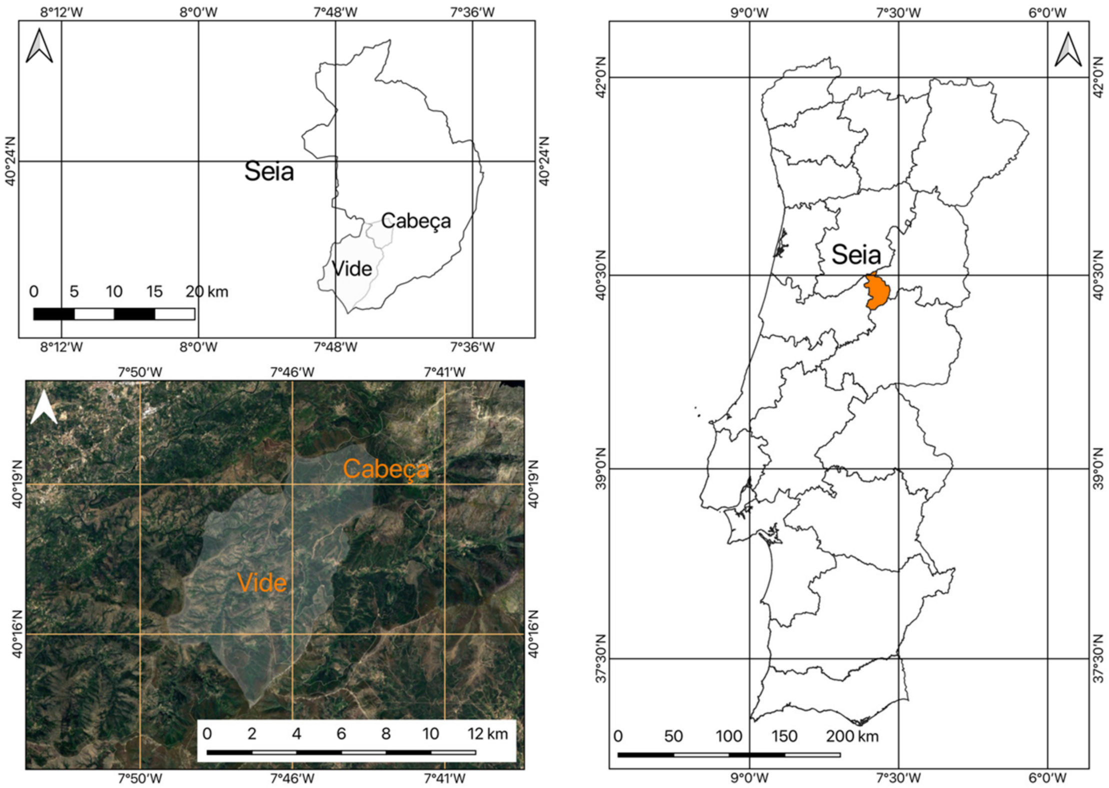

Figure 3. Location of the area under study.

The stands of *A. dealbata* analyzed in this study are visible from the road that connects Casal do Rei to Cabeça, located on the opposite slope of the Ribeira de Loriga valley, as shown in Figure 4.

2.2. Framework of the Area under Study

2.2.1. Geology and Geomorphology

The region mainly consists of extensive granite outcrops, aged between 340 and 280 million years, interspersed with metamorphic rocks, such as shale and graywacke, aged between 650 and 500 million years. These dominant geological formations are intercepted by numerous veins of quartz, granitic pegmatites, and dolerites. In the granite areas, the landscape is dominated by extensive plateaus that are bounded by steep slopes. In these areas, watercourses take advantage of the existing network of tectonic faults and fractures, presenting straight lines. In places where the action of glaciers was felt, erosive forms can be observed, as well as deposition structures. In areas that are not covered by the ice masses, the characteristic features of granite landscapes are evident from the action of different geological agents, such as water, wind, chemical phenomena, and temperature differences. In the areas where shales and greywackes dominate, which are materials whose impermeable nature facilitates surface runoff, a succession of wavy forms originated through a dense and winding drainage network can be observed.

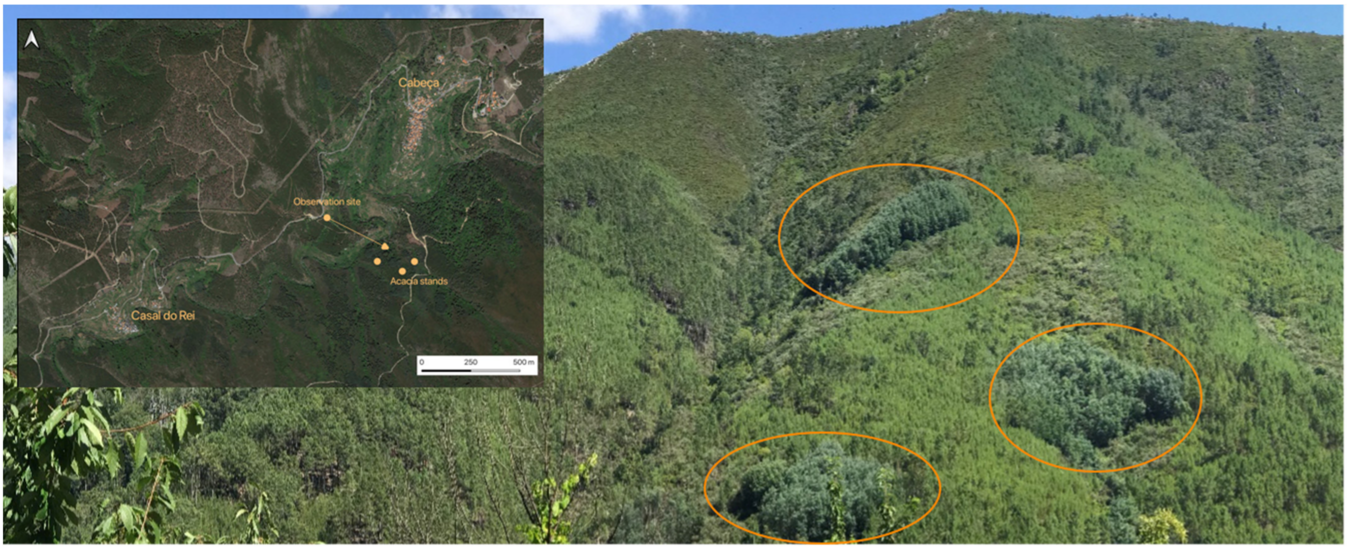

Figure 4. *A. dealbata* stands (highlighted) on the opposite slope to the road that connects Casal do Rei to Cabeça.

2.2.2. Climatology

Regarding the climatological characterization, data were searched in the meteorological stations closest geographically to the study area with data that are available on the website of Instituto Português do Mar e da Atmosfera (IPMA). These stations were located in Viseu, Guarda and Castelo Branco. The total absence of thermopluviometric stations in the target area made it impossible to characterize the climate locally. However, there may be significant differences in the conditions observed, mainly due to the difference in altitude at which these thermopluviometric stations are in relation to the target zone. The climatic information for Casal do Rei was simulated through the METEOBLUE platform, available at https://www.meteoblue.com, accessed in 14 January 2021. Figure 5 presents the data collected for the three locations and the data modelled for the target area. The Viseu station is at an altitude of 443 m, with the coordinates 40°39′ N and 7°54′ W. The Guarda station is at an altitude of 1019 m, with the coordinates 40°31′ N and 7°15′ W. The Castelo Branco station is at an altitude of 386 m, with the coordinates 39°50′ N and 7°28′ W. The geographical coordinates of Casal do Rei are 40°31′ N and 7°55′ W and the altitude is 470 m.

Despite the geographic proximity between with Penhas da Saúde weather station, it was decided not to use the data from this station. The influence of altitude, especially during winter, can differ significantly from the conditions that were verified at Casal do Rei. The region has a Mediterranean climate, with two mild seasons (spring and autumn) being separated by two extreme seasons (a hot and dry season, summer, and a cold and wet season, winter). In the case of the Ribeira de Loriga valley, the patterns of precipitation and temperature are further conditioned by the effect of the orientation of the slope and the surrounding relief. Thus, the embedded valley and exposure to the north determine that, in the area selected for the present study, relatively mild temperatures and high humidity are felt.

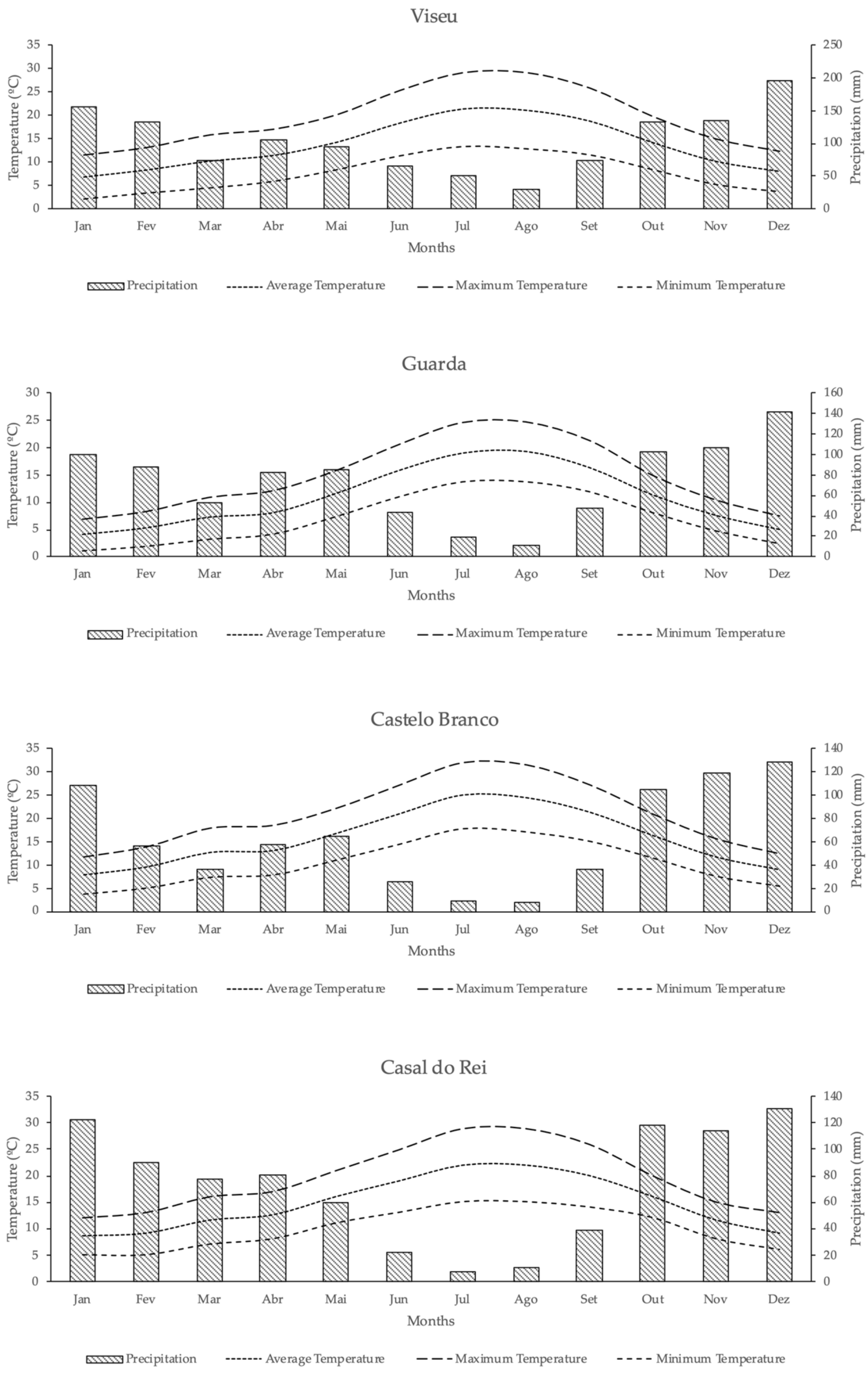

Figure 5. Data that were collected for the three selected stations, Viseu, Guarda and Castelo Branco, and the data modelled for Casal do Rei.

2.3. Study Species

The genus *Acacia* comprises about 1380 species, 1000 of which are native to Australia, with the rest being native to the remaining continents of the Southern Hemisphere, except for a few species that are originally from North America [19]. There are divergences in the classification of the family to which the acacias belong. On the one hand, some of the authors place them in the large family Leguminosae, although some authors claim that it belongs to an independent family, the Mimosaceae [20,21]. Like other leguminous plants, acacia seeds grow in small pods, which open, releasing the seed [19]. Among these many species, there is one that, mainly due to the spectacular nature of its flowers, quickly attracted attention as an ornamental plant. *A. dealbata* presents bright yellow globular inflorescences in bloom [22]. As an essentially Australian species, acacias are very well adapted to hot and dry climates, with the regular occurrence of rural fires, many of which may be designated as pyrophyte species, which is, species for which fire acts as a stimulus for growth and dispersion [22]. Thus, it is seen that, in areas where the climate is hot and dry, as Southern Europe, acacias are very well prepared to compete with native species for resources, such as space, water and nutrients, in addition to having the collaboration of seasonal fires to facilitate dispersion [14].

Humans have been an excellent dispersing agent of species worldwide, and species that were previously restricted to an area can be easily transported to another side of the world. These non-native plants, which are described as exotic, may not even cause significant problems. In fact, in many cases, the new habitat does not have the ideal conditions that the species had in its original habitat. However, sometimes the exotic species have biological characteristics, such as rapid growth, the formation of a more significant number of seeds, alteration of the features of the environment, among others, which make it a formidable competitor in a place where it is not native, beginning to proliferate. In these cases, it becomes an invasive species, and the phenomenon is called biological invasion [23]. In Portugal and most Southern Europe, the most disturbing species are *A. melanoxylon*, *A. longifolia*, and *A. dealbata*, which is the most problematic of all; it forms the most significant clusters and is the species more dispersion [24].

For a long time, *A. dealbata* and other acacias continued to be seen as species of exceptional economic or botanical value. Although observations on their invasive nature were already beginning to be made, it was not until 1937 that the first legislation to control the plantation of *A. dealbata*. However, it only controlled minimum distances for sensitive lands, such as pastures, agricultural crops, or embankments [25,26]. It was only in the 1970s and 1980s that this problem started to be seen as something serious, but, at this time, the main focuses of expansion were related not to plantations, but to forest fires that allow this and other acacias to quickly colonize previously occupied land by native species [27]. Once colonized by acacias, these areas are unlikely to have conditions for native species to develop again, because, in addition to proliferating, creating an extensive seed bank in the soil that allows rapid recolonization in the event of disturbances, such as fires or removal of vegetation, its leaves contain toxic compounds that inhibit the growth of other plants when they accumulate in the soil (a phenomenon called allelopathy [28]), and they mainly change the chemical composition of the soil a lot [29,30].

Some studies that were carried out in Spain and Portugal, where soils with *A. dealbata* and soils occupied with *Quercus robur* were characterized, demonstrated the differences that these soils suffered [31–33]. In these studies, it was found that soils invaded by *A. dealbata* have less biodiversity, are more prone to other exotic species, present fewer ferns and mosses, are richer in nitrogen, and have a more acidic pH [34]. These changes in soils are reflected in the biodiversity, in the water cycle and in all other processes and functions of an ecosystem [35]. The cutting of the acacias combined with herbicides can be a way to control them or be dehulled to cause dehydration. However, given the seed production capacity that these species have, even if all of the plants were uprooted at a given time, there would still be enough seeds to continue to burst for several years [36].

2.4. Data Acquisition

2.4.1. Occurrences of *A. dealbata* Stands in the União de Freguesia de Cabeça e Vide

The data on *A. dealbata* stands in the territory corresponding to the União de Freguesia de Cabeça and Vide were collected using satellite images available on the platform https://www.sentinel-hub.com, accessed on 14 January 2021, which were subsequently processed in the open-source Geographic Information System (GIS) QGIS 3.16 Hannover. The images were collected by the Sentinel-2 satellite during August 2019 and true color L2A images were selected. In these images, *A. dealbata* stands were delimited.

2.4.2. Rural Fires Occurrences

The data relating to rural fires in the União de Freguesias de Vide e Cabeça were obtained through the database of the Instituto para a Conservação da Natureza e da Floresta (ICNF) at http://www.icnf.pt, accessed on 16 January 2021. The data were downloaded in the form of shapefiles and used in GIS QGIS 3.16 Hannover. They were overlaid on the territory boundaries that corresponded to the União de Freguesias de Vide e Cabeça, so that it was possible to visualize the area that is affected by the successive fires in this region.

2.4.3. *A. dealbata* Stand Selection

The area for the study was selected following an accessibility criterion. Afterwards, two circular-shaped parcels were delimited with a radius of 15 m, corresponding to an area slightly larger than 700 m^2 for each one of the parcels. Given the relatively small size of the area, which is approximately 1960 m^2, dispersed over several terraces, and with some difficult to access, there was a slight overlap between the two parcels. Where this overlap occurred, the trees were counted as part of Parcel 1. Subsequently, all the existing trees in each of the parcels were counted, and their relative positions were determined by measuring the distance to the center of Parcels 1 and 2, as shown in Figure 6.

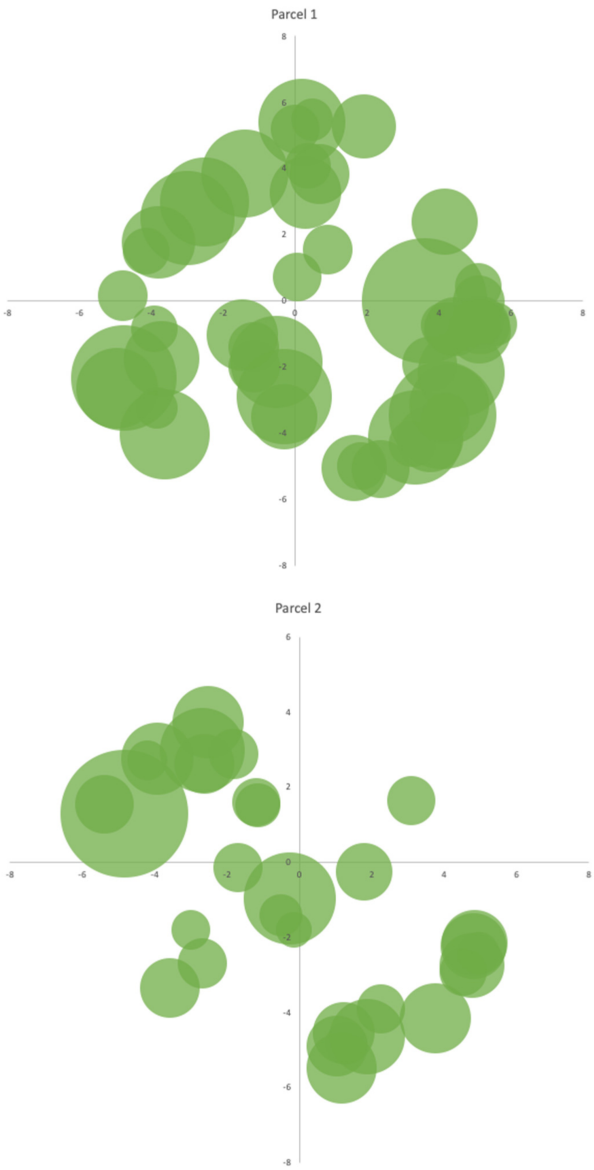

Figure 6. Distribution of *A. dealbata* trees in Parcels 1 and 2.

The diameter at breast height (DBH) was also measured for all trees. This diameter was determined as the average between the largest and smallest diameters that were measured at 1.30 m from the ground. Using the DBH measurement, it was possible to classify the trees into categories. Thus, eight classes were defined according to the following intervals:

- Class 5—DBH less than 5 cm;
- Class 10—DBH between 5 and 10 cm;
- Class 15—DBH between 10 and 15 cm;
- Class 20—DBH between 15 and 20 cm;
- Class 25—DBH between 20 and 25 cm;
- Class 30—DBH between 25 and 30 cm;
- Class 35—DBH between 30 and 35 cm;
- Class 40—DBH between 35 and 40 cm.

In Parcels 1 and 2, 83 trees were accounted, with 79 belonging to the species *A. dealbata*, two belonging to the species *Pinus pinaster*, and two others belonging to the species *Arbutus unedo*. The classification within the representative classes of the DBH was only carried out for the specimens of the species *A. dealbata*, since this was the species of focus. After counting, locating, and framing the existing specimens in the parcels, samples were selected to represent each of the classes. In cases where it became difficult or impossible to collect the chosen specimens, they were replaced by other specimens that were considered equivalent; first, because they had the same diameter class, and, second, for presenting a similar morphology in aspects, such as height, canopy width, and density of branches and foliage. The trees were cut as close as possible to the ground, using chainsaws that were operated by Forest Sappers. The measurements, namely, the height of the trunk, the height of the crown, the diameter of the crown, the weight of the trunk, and the weight of the branches and foliage were then made. Slices of the trunks were also collected, with a thickness of approximately 2 to 3 cm to determine the age of each specimen.

3. Results and Discussion

3.1. Occurrences of A. dealbata in the União de Freguesias de Vide e Cabeça

The *A. dealbata* stands that, in the União de Freguesias de Vide e Cabeça, are of a dispersed nature and occur exclusively in areas that have already been affected by rural fires. These stands, which can still be considered negligible, represent about 11.85 ha in a territory of about 5647.41 ha. However, the potential for expansion is high, given the number of dispersed stands that have already been identified, with 40 throughout the territory, but with a preferential concentration, in number and size, in the territory of the former parish of Cabeça. In this area, stands are located on the opposite hillside to the villages of Cabeça and Casal do Rei, with several stands exceeding 2000 m^2 (Figure 7).

3.2. Occurrences of Rural Fires in the União de Freguesias de Vide e Cabeça

There is already a long history of rural fires in the União de Freguesias de Vide e Cabeça, with a few years since 1975 for which there were no registered fires. When there were no fires in the region, they occurred nearby, as shown by the overlapping of the burnt areas shown in Figure 8. Of all the occurrences verified, the periods in which the largest fires occurred was in 2005, followed by 2017. The difference between the two occurrences is that, in 2017, the fire only stayed in the territory of Vide and did not reach Cabeça. In 2005, the fire hit the two territories violently, but fires in the decade from 2000 to 2009 did not stop with the occurrence in 2005, since, in 2001, 2002, 2003, and 2004, fires also plowed through the slopes of Cabeça and Vide in such a way that practically the only parts of the territory that did not burn were the urbanized parts and those where agriculture did not allow the accumulation of fuel. After a period in which there was an extensive occurrence, which affected a significant part of the territory, the probability of new occurrences in subsequent years decreased, most likely because an extended period was necessary for the fuel load to recover, as can be seen in the sequence of overlaps.

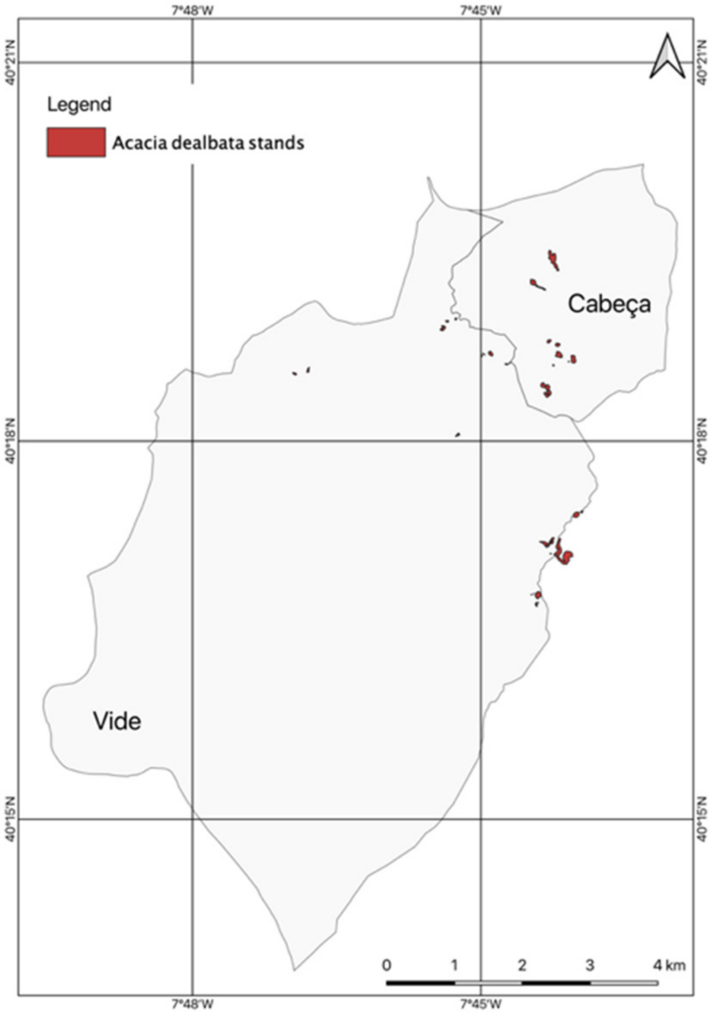

Figure 7. The areas occupied by *A. dealbata* stands in the União de Freguesias de Vide e Cabeça.

However, this reality can change, since invasive species, such as *A. dealbata* (and others already identified in the area under study, such as *Hakea sericea*), can react rapidly in the post-fire period, producing large amounts of biomass. This ability to recover may contribute to the increased risk of rural fires occurring, mainly by reducing the recovery period between occurrences that were directly related to the recovery capacity of native species. It should be remembered that the study area is on the slope of Serra da Estrela and is, therefore, a terrain in altitude, where low temperatures may occur and associated with poor soils, do not constitute an environment that is conducive to the exuberance of vegetation. The major milestone regarding the occurrence of rural fires in the region was the year 2005, which was marked in the local population memory. 2005 was a dark year for the municipality of Seia, with a total of 276 fires and a total burnt area of 17,260.95 ha. That is, 39.62% of the territory of the municipality was directly affected by rural fires. Concerning União de Freguesias de Vide e Cabeça, in the period between 1975 and 2018, it was found that practically the entire region was at some point burnt. In Figure 9, the overlap of all areas that are affected by rural fires can be seen. As shown, only urbanized areas occupied by the villages of Cabeça and Casal do Rei were not affected.

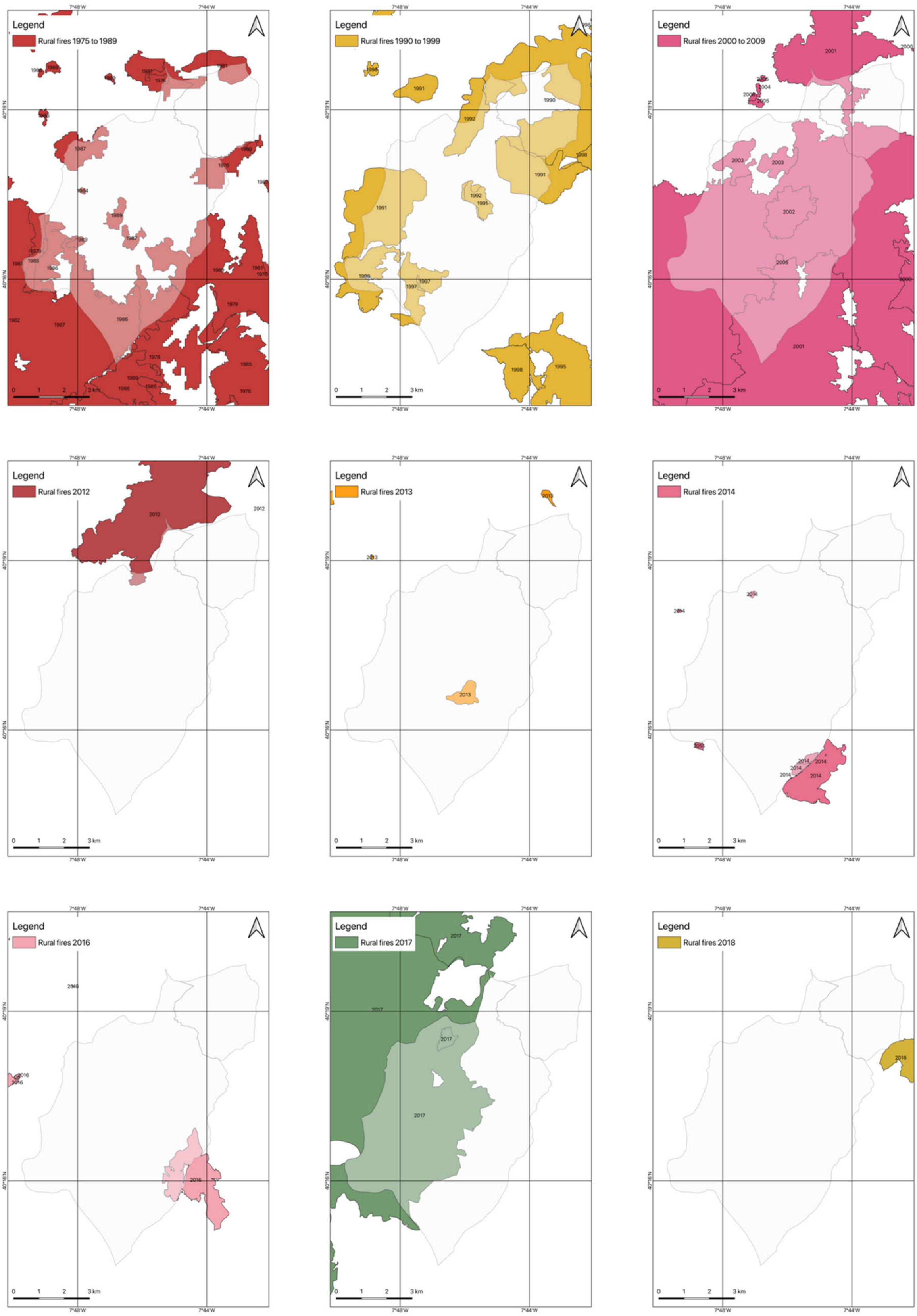

Figure 8. Burnt areas between 1975 and 2019 in União de Freguesias de Vide e Cabeça.

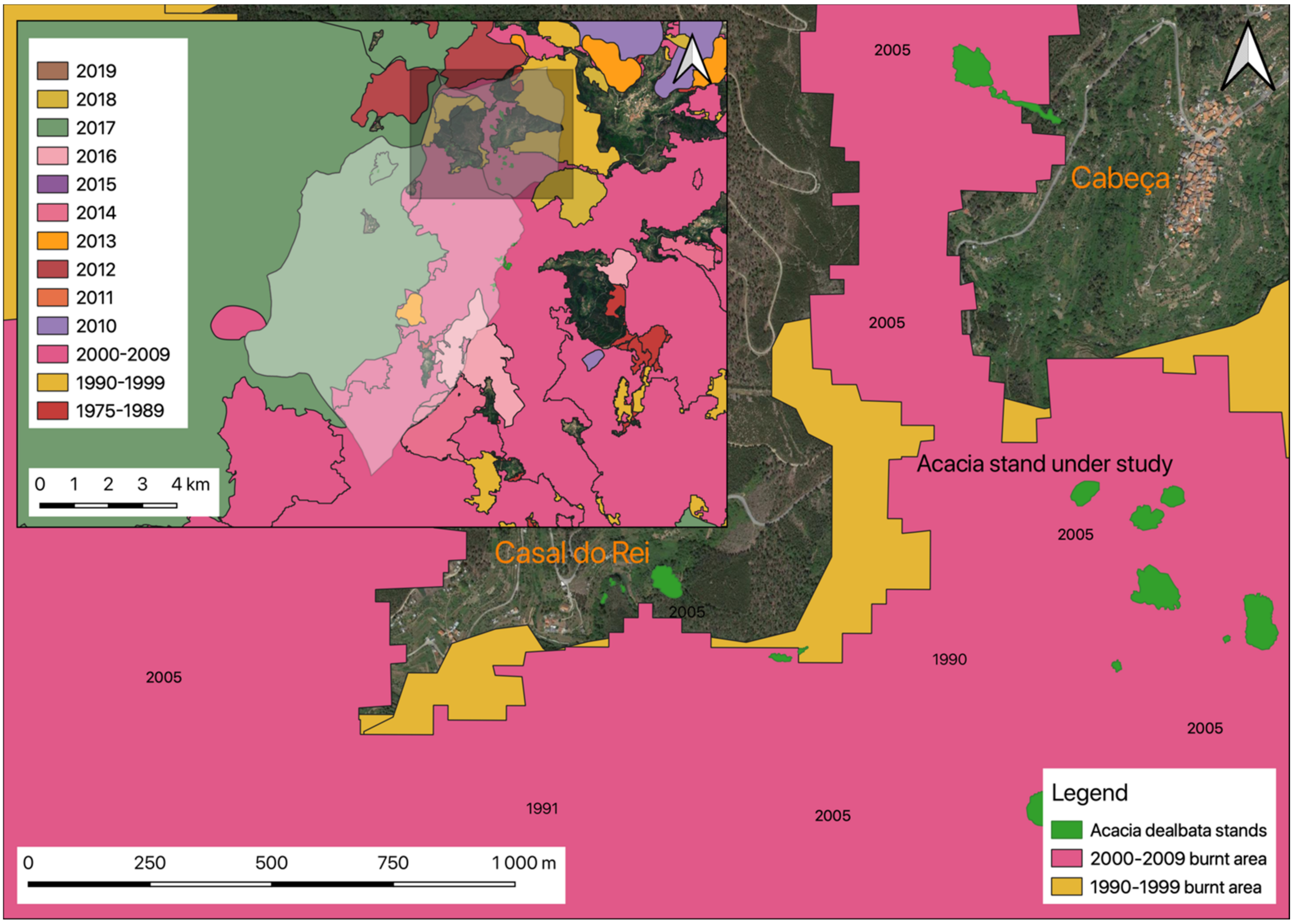

Figure 9. Overlapping of the burnt areas in 1975–2019 in União de Freguesias de Vide e Cabeça.

3.3. The Productivity of A. dealbata in the Casal do Rei Region

The samples of *A. dealbata* selected in Parcels 1 and 2 were processed, as described in Section 2.4.3. The slices collected (Figure 10) were used to determine the age of the trees. The height of the trunks and tree crowns were measured and the weight of all the material, obtaining the results that are shown in Table 1.

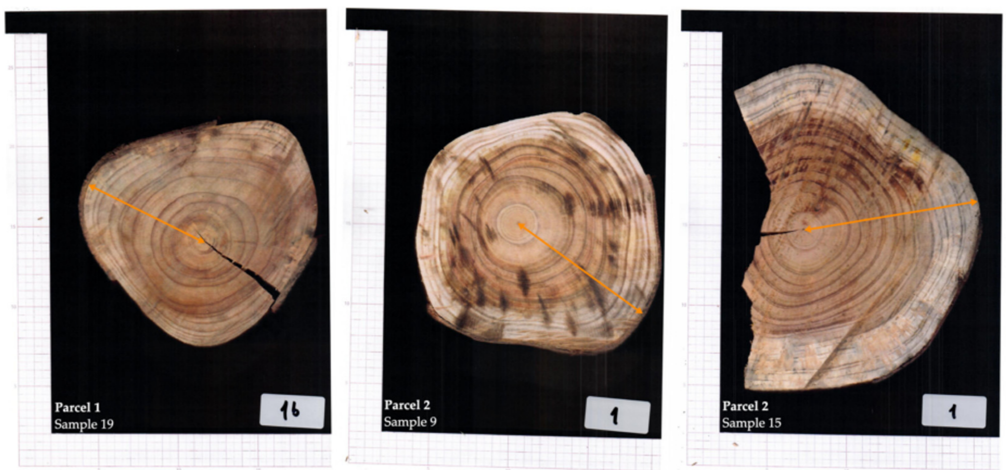

Figure 10. Slices used in the age determination of the specimens by counting the growth rings.

Table 1. Measurements and annual biomass increment calculated for the samples collected in Casal do Rei.

Parcel	Sample	DBH Class	Height (m)	Canopy Diameter (m)	Growth Start Year	Age (Years)	Total Weight (kg)	Annual Biomass Increment (kg.year^{-1})
1	3	15	23.6	1	2008	10	54.6	5.5
	5	10	15.4	1	2013	5	28.8	5.8
	6	10	13.2	2.1	2004	14	33.5	2.4
	8	30	22.9	9.5	1998	20	594.8	29.7
	16	10	18.5	2	2008	10	47.8	4.8
	17	10	11.3	2.5	2009	9	18.5	2.1
	19	15	17.9	4.3	2006	12	166.8	13.9
	26	20	25.1	1.2	2004	14	249.1	17.8
	29	5	9.9	1.8	2012	6	4.1	0.7
	30	10	23.7	1	2009	9	45.5	5.1
	33	15	23.4	3.8	2004	14	223.9	16.0
2	9	15	19.9	3.4	2003	15	138.9	9.3
	10	10	15.7	1.9	2008	10	40.7	4.1
	11	5	12.5	1.9	2009	9	13.6	1.5
	15	25	32.7	2.65	2001	17	333.4	19.6
	21	20	10.3	3.2	2006	12	19.7	1.6

With the data acquired, the annual biomass increment was calculated expressed in kg.year^{-1}. Some of the specimens with ages prior to the tremendous rural fire of 2005 were found, most likely because they are in a more secure location on the slope, being closer to the watercourse that runs nearby (Ribeira de Loriga). These also correspond to the larger specimens; namely, sample 8 from parcel 1, with a total height of 22.9 m, a total weight of 594.8 kg and an age of 20 years; sample 26 from parcel 1, with a total height of 25.1 m, a total weight of 249.1 kg and an age of 14 years; sample 33, of parcel 1, with a total height of 23.4 m, a total weight of 223.9 kg and an age of 14 years old; sample 9 from parcel 2, with a total height of 19.9 m, a total weight of 138.9 kg and an age of 15 years; and, sample 15 from parcel 2, with a total height of 32.7 m, a total weight of 333.4 kg and an age of 17 years. Despite having started its growth prior to 2005, the only specimen that did not show the same rates of development was sample 6 of parcel 1. Although its development in height was in line with the other specimens at 13.2 m, it did not maintain the same development concerning the annual biomass increase, since its total weight of 33.5 kg only represents an annual biomass increase of 2.4 kg.year^{-1}.

The average value of the annual increase in biomass that was observed for the different specimens was 8.73 $\pm$ 4.09 kg.year^{-1}. Other studies, such as the one that was conducted by Albaugh et al. (2017) in Chile on the use of *A. dealbata* and *Eucalyptus globulus* as energy crops, reached values of 2.4 kg.year^{-1} for plantations of 15,000 trees.ha^{-1}, with a total of 108 t.ha^{-1}, with a rotation of three years, while, for a plantation of 5000 trees.ha^{-1}, obtained an annual biomass increment of 5.05 kg.year^{-1} [37]. Another study, which was conducted by Gouws and Shackleton (2019) in South Africa, determined a value of 0.57 kg.year^{-1} for the annual increment in biomass, with planting densities of 7000 trees.ha^{-1} [38]. This difference in values is particularly noticeable for the case study that was carried out in South Africa, since, in the case of the study carried out in Chile, for a plantation density of 5000 trees.ha^{-1}, the presented values are within the confidence interval calculated. These differences may be related to the levels of rainfall recorded in different locations, since the growth of *A. dealbata* is directly related to the access to water, as shown by Hunt and Beadle (1998), Forrester et al. (2010), or Vertessy et al. (2001) [39–41].

The dispersion of *A. dealbata* is being enhanced by the increase in occurrences of forest fires in the study area. From Sentinel-2 satellite images analysis, as shown in Figure 11, in the year immediately after the 2005 fire (more specifically in October 2006), the vegetation was emerging. However, according to the testimony of local inhabitants, there are visible patches of trees as they existed, who reported a continuous patch of dense pine forest up to a certain level. From that level upwards, the vegetation decreases in size, with a predominance of shrub species, such as *Cytisus striatus*, until this also disappears and gives rise to smaller species, such as *Erica australis*. In the following images, which were obtained in May 2013, August 2017, and May 2019, the vegetation is slowly recovering. However, recovery by *A. dealbata* is much faster than any other species, only contrasted by the occurrence of some eucalyptus that competes for the best area with *A. dealbata*.

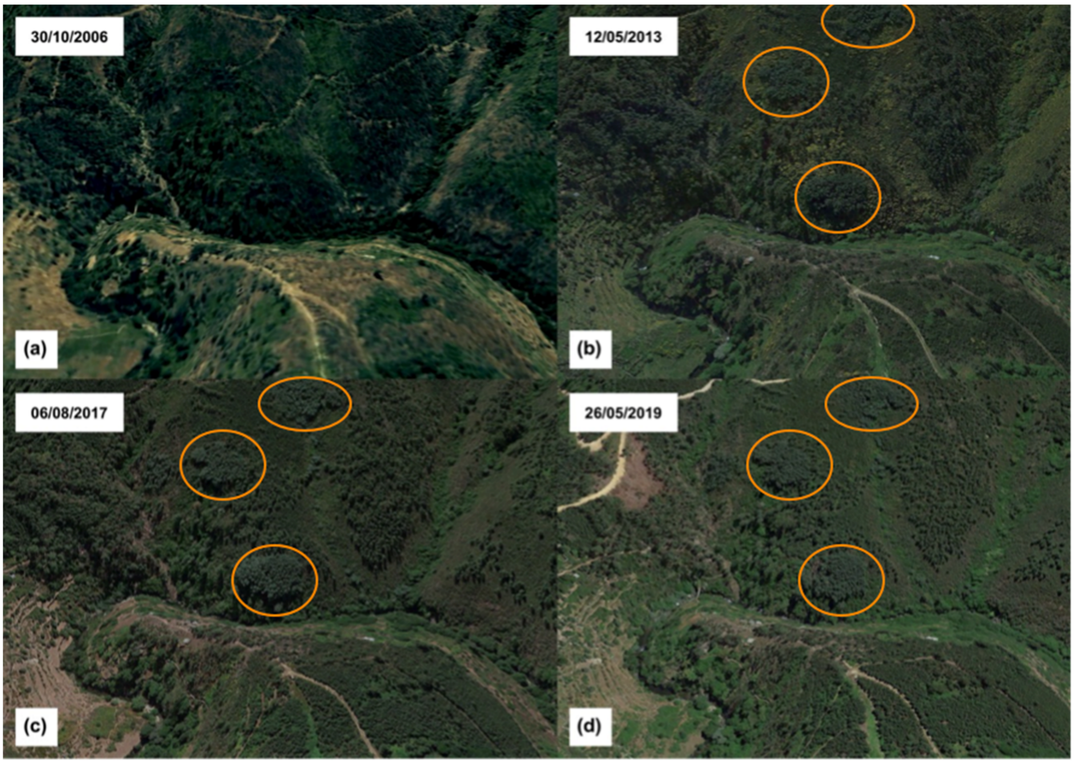

Figure 11. Sentinel-2 satellite images of the *A. dealbata* stands located on the opposite slope to the villages of Cabeça and Casal do Rei. (**a**) image obtained on 30 October 2006; (**b**) image obtained on 12 May 2013; (**c**) image on 6 August 2017; and, (**d**) image obtained on 26 May 2019. The observation positioning was chosen to reflect the same view used in the previous Figure 4.

As seen in the satellite images, *A. dealbata* is the only species showing an increasing development, since it is the only species that started its growth immediately after the fire. One year after the fire occurred in the summer of 2005, *A. dealbata* already has a set of stands that remain until today, as can be seen in the satellite image of October 2006. However, the high density that is caused by the initial fast growth also led to discrepancies in each tree, varying in accordance with its exposure to sunlight, which is reason why trees that started growing in the same year do not show the same development since those that acquire the status of dominance do not allow others to grow at the same rate.

This reaction to fire is in accordance with the studies that were carried out by Bowd et al. (2019), which point to fire as one of the auxiliaries that benefit the dispersion of *A. dealbata* in a study on long-term changes in soils that were caused by fire, as well as in previous studies, such as that carried out by Je (2006), where the fire management impacts on invasive plant species in the western United States is analyzed [42,43]. Another study, which was carried out by Florentine et al. (2008), points to fire as the activating process that awakens seeds in pyrophyte species [44]. Gordon et al. (2017) addressed the response of species of the genus *Acacia* to high severity fires, indicating the regeneration potential of these species in the post-fire period [45,46]. The results that were observed in Casal do Rei show a capacity for recovery from fire superior to other species, mainly concerning the natives, since they may find competition from other exotic species, such as *Hakea sericea*, which has already been observed in the vicinity of these stands. This capacity for growth and area occupation is visible in Figure 12, which was captured on March 15, 2021, where the *A. dealbata* stands photographed from the same observation point used in Figures 4 and 11, show a progression mainly following the water lines. This occupation of the water lines is, most likely, related to the fact that the seeds are dragged by rainwater and because those are areas where the humidity is higher, thus enhancing their development.

Figure 12. Stands of *A. dealbata* (photo obtained on 15 March 2021). The yellow color of the flowers makes the identification of the stands evident. It is possible to observe the development of the stand in the waterline.

4. Conclusions

Biological invasions are a problem that intensively affects ecosystems, mainly when associated with other factors, which may have a supporting effect on the dispersion of invasive species. One of these factors is fire, which, in in the case of *A. dealbata*, operates as a disruptor for its dispersion and as an activator of its germination. Being a heliophilous species, *A. dealbata* benefits in the first moment with the elimination of the vegetation cover, with, in a second moment, the seeds to be activated by the fire itself, promoting germination and a quick conquer of the space. In Portugal, the productivity of *A. dealbata* is high when compared with other stands in different latitudes, such as South Africa or Chile, and very high when compared with the Portuguese native species, with which competes for area and nutrients with a clear advantage, as was verified in this study. Thus, it can be concluded that fire is an enhancing agent for the expansion of *A. dealbata* with the area that is occupied by this species growing significantly in recent years, following the trend of an increasing number of rural fires. This results from several factors, e.g., climate change and the abandonment of agriculture and forest land.

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CHAPTER 3 – Spread of Invasive Species

Chapter Index

environments

MDPI

Review

Fire as a Selection Agent for the Dissemination of Invasive Species: Case Study on the Evolution of Forest Coverage

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Abstract: Climate change has enhanced the occurrence of rural fires, since changes in the hydrological cycle have led to the occurrence of increasingly long and frequent periods of drought. This recurrence of rural fires in Portugal, in turn, has led to the successive elimination of vast areas traditionally occupied by native species or species of economic interest, which are being successively replaced by new species with invasive behavior. Among these, *Acacia dealbata* stands out for its dispersion capacity and for the area it has already occupied. In the present work, which reviews the evolution of forest cover over the last 18,000 years in the Serra da Estrela Natural Park, we intend to demonstrate that fire acts as a species selection agent and that it enhances the development of heliophile and pyrophyte species. For this purpose, an area of the municipality of Seia was selected, more specifically Casal do Rei, where the development of *Acacia dealbata* forests is monitored. In the end, it was concluded that, in fact, by analyzing the ages of the specimens present in these populations, fire acts as a selection agent by freeing up the space previously occupied by other species, opening the way for the growth of heliophiles and pyrophytes invasive species while enhancing their germination.

Keywords: invasive species; *Acacia dealbata*; rural fires; forest management; rural development

1. Introduction

Ecosystems are currently facing intense pressures related to changes driven by climate change [1–4]. However, species do not react in the same way to these adaptations, since not all respond equally to different stimuli, such as the increase in the average temperature of the air, decrease in the levels of humidity of the air, increase of the periods of drought, decrease of the precipitation, and alterations in the cycle of the seasons, among others [5–8]. This inability to react or difficulty in reacting to new conditions leads to a change in the ecosystem balance over time, and in this way, ecosystems evolve according to the new conditions, which is often the reason why traditional species are replaced by others that are more adapted to these new conditions [9–11].

Usually, it is in these scenarios that some species find the opportunity to become predominant, especially when exotic species which may acquire invasive behavior are present in ecosystems [12,13]. In this way, these species will occupy the niches left vacant by the native species, often becoming dominant, relegating native species to a secondary role in the occupation of physical space and changing the balance in the inter-species relationships [14,15]. Obviously, this type of change will cause imbalances at all levels and in all relationships within the ecosystem, leading to a development that favors the needs of the new dominant species [16].

Fire is an element that has always been present in the Mediterranean landscape, being an integral part of the phenomena that shaped both the landscape and the species that developed and evolved in this environment [17–19]. However, as a consequence of climate change, there has been an increase in the occurrence of extreme climatic phenomena, including profound changes in the hydrological cycle and the subsequent occurrence of periods of more frequent and prolonged drought [20,21]. This factor, associated with the presence of a set of exotic species of a pyrophyte characteristics, leads to an artificial selection of species by fire, which will contribute to the replacement of traditional indigenous species, since pyrophyte species take advantage of the openings created by fire to quickly develop and conquer the space previously occupied by native species [22,23].

This fast growth of exotic species, in relation to native species, is decisive for progressively replacing the vegetation cover. In the case of forest cover, this substitution of native species by exotic pyrophyte species, in addition to the losses associated with biodiversity and with the relationships previously established in the ecosystem, may be associated with the destruction of production crops, such as, for example, *Eucalyptus globulus* plantations for the pulp industry, or *Pinus pinaster* for the wood pellet industry, since, due to the rapid growth they present nd the aggressiveness with which occupy the physical space, would enter into direct competition with these species already installed, leading to their development being affected and to subsequent losses in productivity [24–29]. In Portugal, one of the species that stands out the most for its invasive behavior and for the proliferation that has occurred in recent years is *Acacia dealbata*, which has been occupying more and more area from year to year, forming dense forests where no other species can survive; such is the density that this species can develop and present [30]. At present, again under the influence of changes in the climate, and with the triggering of associated phenomena, such as the occurrence of long periods of drought and a subsequent increase in the recurrence of rural fires, the forest cover is also changing [31–33]. This is causing an artificial selection of species, where pyrophyte species, mostly exotic, such as *Acacia dealbata*, gain an advantage and take up more and more area at the expense of native species.

This study presents a review on the sequence of the development of forest cover in the region during a period that comprises the last 18,000 years, during which there was a stabilization of the different forest species, followed by the presentation of a case study in which the developments in the forest cover that occurred in the last two dozen years are analyzed. It is assumed that the increase in the recurrence of rural fires in the region causes changes in the structure of the forest cover through the selection of species by fire, namely one species in particular, *Acacia dealbata*, which stands out for the area that it already occupies. An analysis of the occurrence of rural fires in the region and the impact on the current state of forest cover was made using the information available in databases, namely those at Instituto Português do Mar e da Atmosfera (IPMA) for climatological data and by Sistema Nacional Informação Geográfica (SNIG) for georeferenced data on occurrences of rural fires. Information made available by the press on rural fires in the region was also collected, as was information from interviews with the inhabitants of Cabeça and Casal do Rei, about the perception of the evolution of the climate in the region and on the severity of rural fires that occurred in the past. Some of the methods currently used to control *Acacia dealbata* are also presented.

2. Geophysical and Biophysical Framework of the Area under Study

2.1. Location and Limits

The area selected for this study is located on a mountain slope in front of the village of Cabeça and the village of Casal do Rei. Both locations belong to the Union of Parishes of Vide and Cabeça in the municipality of Seia and the district of Guarda. Figure 1 shows the location of the target area and its regional and national context.

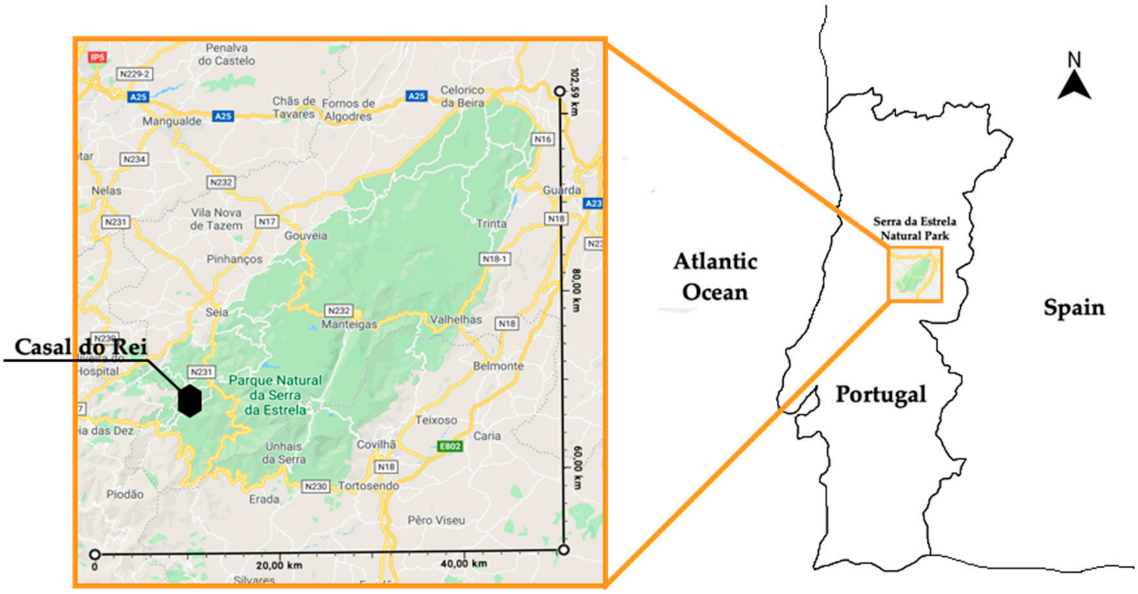

Figure 1. Location of the target area and its regional and national context.

The *Acacia dealbata* groves considered in this study, as already mentioned, are visible from the road that connects Casal do Rei to Cabeça, located on the opposite slope, on the other side of the valley, where the Loriga stream runs, as can be seen in Figure 2.

Figure 2. *Acacia dealbata* groves on the slope opposite the road from Casal do Rei to Cabeça. Acacia groves are identifiable by their very characteristic greenish color.

2.2. Hydrography

The Serra da Estrela Natural Park covers two hydrographic basins, the Tagus River and the Mondego River [34]. Three important Portuguese rivers begin in the Serra da Estrela Natural Park—Mondego, Zêzere, and Alva [35]. The Mondego River is the largest Portuguese river with a hydrographic basin entirely in national territory [36]. The Alva River is one of the most important tributaries of the Mondego River, which has its source in Serra da Estrela, located near Sabugueiro, in the Rossim Valley area, at approximately 1500 m elevation [37]. The Zêzere River is the largest tributary of the Tagus River in Portugal, beginning in the middle of the glacier valley in the heart of the Serra da Estrela, at Covão d'Ametade (at about 1900 m elevation). In its upper course, upstream of Manteigas, it traverses a typical glacier valley with a U-section [38]. In the central area of the massif, there are several lagoons of glacial origin, some of which have been used for the construction of multi-purpose projects, with emphasis on hydroelectric power plants. The area under study is located on the left bank of the Loriga stream, one of the tributaries of the Alva River, which is formed by the union of the Nave stream and the São Bento stream [39].

2.3. Geomorphology

The geomorphology that characterizes the region essentially derives from tectonic displacements, which lifted the mountain from the surrounding plateaus and pushed it towards the Northeast [35]. The cliffs that limit it are fault cliffs with a relatively long evolution, which must have given rise to the mountain [40]. However, the great gaps that are observed in Serra da Estrela are not only due to tectonic movements, but also due to the deep indentations of the rivers, induced by the rising of the mountain itself from the marginal plateaus [41]. The forms of the relief can have very different origins. Some depend on the nature of the rocks, and others are related to much colder climates than the current one, particularly when the temperature dropped by at least 10 °C around twenty thousand years ago, giving rise to vast glaciers in the highest part of Serra da Estrela [39]. These climates left remarkable geomorphological testimonies, translated as U-shaped valleys, glacial circuses, lagoons, moray deposits, and erratic blocks, constituting the main originality of the physical landscape of the Natural Park [42].

2.4. Geology

The geology of the Serra da Estrela is dominated by the occurrence of hercynitic granitic rocks, which intruded the pre-Cambrian and Cambrian metasediments that constitute the grauvachic schist complex [43]. These rocks have a varied mineralogical composition, from granodiorites to leucogranites [44]. The area under study is essentially made up of schist terrain and, to a lesser extent, fluvial sedimentary deposits. The schists belong to the Malpica do Tejo formation and are between 500 and 650 million years old [45]. In these rocks, there are some quartz veins of reduced thickness and extension [46]. The river deposits, of recent age, are found along the bed of the Loriga stream, have a very reduced width and thickness, and are mainly composed of blocks and rolled pebbles (of different lithologies and dimensions) and sands [47].

2.5. Pedology

The soils in the area selected for the present study are mostly lithosols, which evolved into cambisols in some places where terraces were built, which were used and still are used in some places for agro-silvo-pastoral activity [48,49]. In the places where the activity stopped, the bushes and the forest slowly occupied the space, and these terraces are currently covered with spontaneous vegetation [50].

2.6. Climatology

A data search was then carried out on the meteorological stations geographically closest to the target area. Data were available on the website of IPMA (Instituto Português do Mar e da Atmosfera), which included Viseu, Guarda, and Castelo Branco, since the total absence of thermopluviometric stations in the target zone made it impossible to characterize the current climate in the locality, and only a comparison with these stations located nearby was possible. However, it should be noted that there can be significant differences in the conditions observed, mainly due to the different elevations at which these thermopluviometric stations are in relation to the target zone. Casal do Rei is about 42 km from Viseu, 49 km from Guarda, and 58 km from Castelo Branco.

For values corresponding to Casal do Rei, METEOBLUE (https://www.meteoblue.com) was used and the data modeled are shown in Table 1 and Figure 3. In fact, as can be seen, using the values modeled for Casal do Rei, although minimum negative minimum temperatures have always occurred during the winter months, it was observed and verified that these occurrences have decreased, although there is a dispersion of these occurrences for months other than the usual ones. It is also verified that, although periods with minimum temperatures have decreased and temperatures have risen, some phenomena that can be considered extreme occur, in which the minimum temperatures can fall below the values considered normal, and often outside the usual months. It is also verified that in the summer months, the maximum temperatures have been successively showing higher values, complemented by a decrease in the values of precipitation, which in recent years has been observed to be nonexistent, increasing the probability of the occurrence of rural fires as conditions become ideal for their proliferation.

Table 1. Summary table of data collected on the website of IPMA (Instituto Português do Mar e da Atmosfera) for the three selected stations, namely, Viseu, Guarda, and Castelo Branco, due to the proximity to the target area, and of the data modeled for Casal do Rei using the platform METEOBLUE. $T_{average}$ represents the average temperature, T_{max} represents the maximum temperature, T_{min} represents the minimum temperature, and $P_{average}$ represents the average precipitation.

Station	Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Viseu Location: 40°39′ N 7°54′ W Altitude: 443 m	$T_{average}$ (°C)	6.9	8.4	10.3	11.5	14.3	18.4	21.4	21.1	18.8	14.2	10.2	8.1
	T_{max} (°C)	11.6	13.2	15.9	17.1	20.2	25.4	29.2	29.2	25.9	19.8	15.0	12.4
	T_{min} (°C)	2.2	3.5	4.6	6.0	8.5	11.5	13.5	13.0	11.7	8.5	5.3	3.8
	$P_{average}$ (mm)	155.7	133.6	74.8	105.2	95.9	66.0	50.5	30.6	75.2	133.2	135.9	195.4
Guarda Location: 40°31′ N 7°15′ W Altitude: 1019 m	$T_{average}$ (°C)	4.0	5.2	7.2	8.0	11.6	15.9	19.1	19.4	16.4	11.3	7.5	4.9
	T_{max} (°C)	6.8	8.2	10.8	12.0	15.7	20.5	24.5	24.6	21.2	14.8	10.3	7.4
	T_{min} (°C)	1.2	2.0	3.3	4.2	7.4	11.0	13.7	13.7	11.9	8.1	4.8	2.5
	$P_{average}$ (mm)	100.1	87.4	53.3	83.1	84.9	43.4	19.6	11.0	47.5	103.2	106.7	141.8
Castelo Branco Location: 39°50′ N 7°28′ W Altitude: 386 m	$T_{average}$ (°C)	7.9	9.6	12.7	13.1	16.8	21.0	25.0	24.4	21.3	16.3	11.7	9.0
	T_{max} (°C)	11.8	14.0	18.0	18.6	22.3	27.3	32.1	31.6	27.3	21.0	15.7	112.5
	T_{min} (°C)	3.9	5.2	7.5	8.0	11.2	14.6	17.9	17.2	15.2	11.6	7.7	5.6
	$P_{average}$ (mm)	108.0	56.7	36.9	58.1	65.1	25.2	8.9	8.4	36.5	105.5	118.8	128.2
Casal do Rei Location: 40°31′ N 7°55′ W Altitude: 470 m	$T_{average}$ (°C)	8.5	9.0	11.5	12.5	16.0	19.0	22.0	22.0	20.0	16.0	11.5	9.0
	T_{max} (°C)	12.0	13.0	16.0	17.0	21.0	25.0	29.0	29.0	26.0	20.0	15.0	13.0
	T_{min} (°C)	5.0	5.0	7.0	8.0	11.0	13.0	15.0	15.0	14.0	12.0	8.0	6.0
	$P_{average}$ (mm)	123	90	77	81	60	22	7	10	39	118	114	131

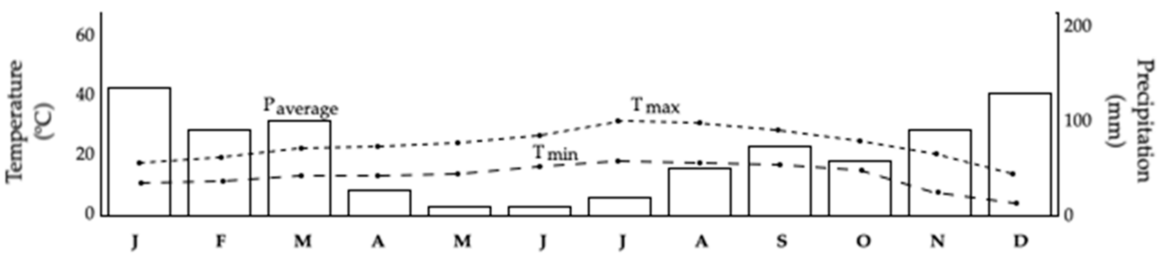

Figure 3. Air temperature and precipitation based on the information available in Table 1 for Casal do Rei using the values modeled with METEOBLUE (https://www.meteoblue.com). In the figure, the maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation are represented.

Despite the geographical proximity between the area under study and the Penhas da Saúde weather station, we decided not to use the data from this station, since in this specific case, the influence of elevation, especially during winter, can result in significantly different effects compared to the real conditions observed in Casal do Rei. Therefore, we opted for the use of data related to the weather stations of Viseu, Guarda, and Castelo Branco since they present conditions closer to the reality observed in Casal do Rei. For example, in conversations with permanent residents in Casal do Rei and in Cabeça, in response to the question about how often it snowed in both locations, everyone replied, "Now, almost every year, snow falls, but it only serves to kill the pests and rarely stays for long periods". They also replied, "It used to be different," and "Sometimes, we stayed closed in for weeks down here (Casal do Rei) because cars did not pass with the snow up there", thus indicating certainty that snow did not accumulate at the bottom of the embedded valley that comprises the Loriga stream. This information is in line with the data that were collected on the website of IPMA (Instituto Português do Mar e da Atmosfera) (www.ipma.pt).

In general, the region has a Mediterranean climate, with two mild seasons, spring and autumn, separated by two extreme seasons, one hot and dry (summer), and the other cold and wet (winter) [51,52]. The patterns of precipitation and temperature are, in the case of the Loriga stream valley, further conditioned by the effect of the orientation of the slope and the surrounding relief [53]. Thus, the embedded valley and the exposure to the North determine that, in the area selected for the present study, relatively mild temperatures and high humidity are felt.

3. Evolution of Vegetation Cover

The oldest mountainous deposits in the entire central cordillera date back to the late glacial period (around 13,000 years ago) and are found only in Serra da Estrela, the most western part of the entire central mountain range [50,54].

According to the fossil records found, the genus *Pinus* is the most represented in the interior of Serra da Estrela, indicating the presence of pine forests (probably in areas of microthermal climate, forming both open and dense forest structures) at medium to low elevations [55,56]. However, as presented by Rubiales et al. (2020), pollen deposits indicate an abrupt change at the beginning of the Holocene (10,350 years ago) in which the genus *Pinus* makes way for other groups of hardwoods adapted to a mesophilic climate or even of a Mediterranean character, such as *Quercus*, or with hygrophilic–microthermal characteristics, such as some species of the genus *Betula*, or species such as *Sorbus aucuparia* or *Frangula alnus* (Figure 4) [55].

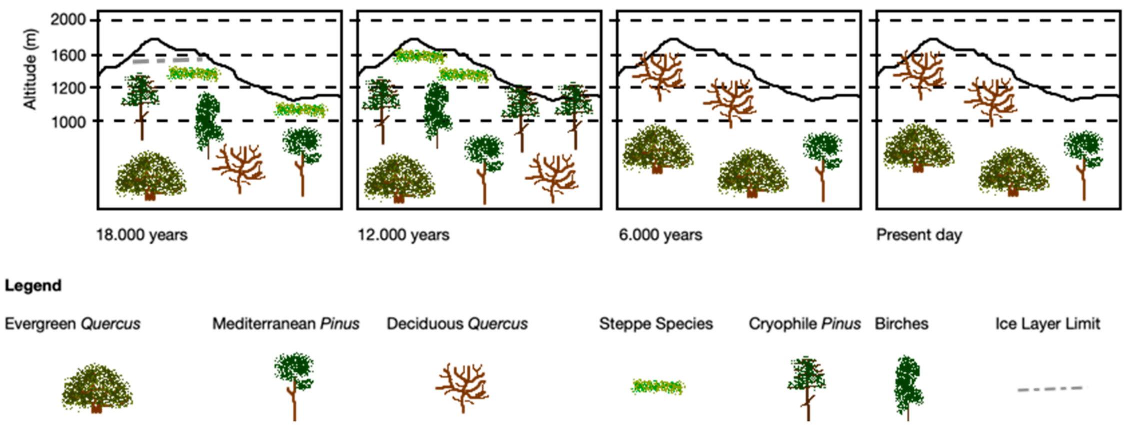

Figure 4. Evolution of pine forests and other woody formations since the last glacial maximum in the different bands of Serra da Estrela (adapted from [55]).

In the innermost strips, already in Spain, the time records, although referring to a much shorter time period than what is available for Serra da Estrela, show a broadly similar pattern during the second half of the Holocene, where pines do not seem to thrive, most likely due to the decrease in the continentality factor [57]. The pollen sequences found, as well as limited plant remnants of larger dimensions, suggest that the genus *Betula* was the dominant and most stable genus [55,58].

The decrease in the population of Casal do Rei has direct impacts on landscape management, mainly due to the abandonment of agro-silvo-pastoral activities on the slopes surrounding the village [59]. The agricultural land, essentially formed of terraces with shale walls, disappeared among the spontaneous vegetation that was growing. In view of the anthropic action, the landscape is currently quite altered in relation to the potential natural vegetation [60]. In fact, in recent decades, there has been a strong focus on maritime pine and eucalyptus stands. The changes associated with the monoculture of these stands result in a worsening of the impact of fire and prevent the installation of several native species, especially those belonging to the most evolved stages of the vegetation cover. However, next to Casal do Rei, there are still some fragments of what the native forest of this landscape would be, albeit in very poor condition [60].

The spontaneous vegetation of the area, altered little by human activity, presents a great complexity and floristic diversity, constituting a residual mark of the potential natural vegetation of the Central region of the country, currently covered mainly by eucalyptus, pine forests, and bush and also by patches of acacias. The forest vegetation is characterized by a dense tree layer dominated by *Prunus lusitanica*, accompanied by *Castanea sativa*, *Viburnum tinus*, and *Arbutus unedo*. Figure 5 presents the current land cover, where the development of acacia groves can be seen.

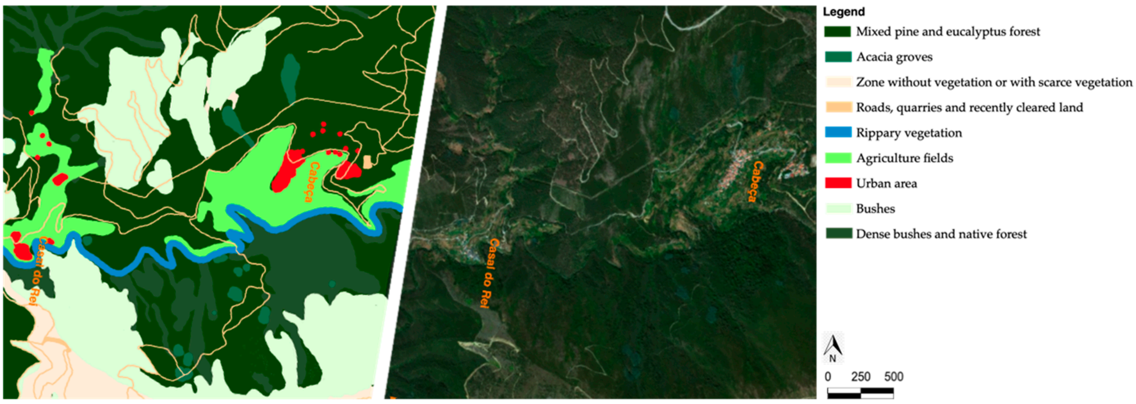

Figure 5. Current land cover in the study area.

Although the potential natural vegetation of the slopes of Casal do Rei belongs to the domain of *Quercus robur* subsp. *broteroana*, there are no well-constituted forests of this species. Instead, the current vegetation is formed by a set of heliophilous scrublands, lashed by recurrent fires that occur in increasingly shorter cycles, which prevents the installation of the slowest growing and most demanding species at ground level [61,62]. Other types of oak, such as *Quercus pyrenaica*, *Quercus suber*, and *Quercus rotundifolia*, also live in the areas with less water retention; the latter is only present on rocky outcrops. However, on the slopes exposed to the North and with high soil moisture, a relic community resists, dominated by *Prunus lusitanica*, which is accompanied by a set of pre-forest shrubs, such as *Arbutus unedo*, *Viburnum tinus*, and *Rhamnus alaternus*, among others, which need to be preserved. These communities are even recognized by the European Community, through the Habitats Directive (92/43/EEC), as a priority habitat for conservation (5230 × pt2) called "*Laurus nobilis* arborescent forests" [63].

However, the recurrence of rural fire favors a vegetation cover dominated by heliophilous shrubs and, when there is a seed bank, an intense regeneration of maritime pine. Among the most frequent shrub communities are *Cytisus scoparius*, *Cytisus grandiflorus*, and *Genista falcata*, as well as the *Ulex minor*, *Erica australis*, *Erica scoparia*, and *Erica umbellata* that normally live on degraded or stony soils [64]. This dynamic becomes difficult to break with an aging population and with poor resources. In addition, the disappearance of the vegetation cover in the post-fire period favors the expansion of invasive alien species such as *Acacia dealbata* and *Hackea sericea*, which, together with depopulation, have all the conditions to thrive [65,66]. With each rural fire, new points of dissemination of these species emerge, spreading in a concentric manner, and thus gradually decreasing the area for native vegetation [65].

4. Impact of Fire on Vegetation Cover

In July 2005, a forest fire reached an area of 17,445 hectares. It severely affected a natural forest of 20 hectares located in Casal do Rei in the Serra da Estrela Natural Park. On 22 July 2005, the newspaper Diário de Notícias, in an article signed by journalist João Fonseca, reported the tragedy that devastated the region, using comments directly from those who experienced the events up close. For example, one of the interviewees stated that, "it can only be arson. Flames appear where and when you least expect them. The firefighters are still extinguishing one and soon another one appears, far or near to the villages, beside the road or in the most inaccessible places, but always where there is thicket and dense forest. This hell seems to have no end. The wonderful forest that was here has all burned." Other witnesses declared that, "thousands and thousands of pine, eucalyptus, oak, and chestnut trees died, but also olive trees, vines, and gardens." Many hectares were destroyed after another fire in this hillside of Serra da Estrela, namely in Senhora da Guia, Pedras Lavradas, Teixeira de Cima, Casegas, Casal do Rei, and Cabeça, mainly composed of eucalyptus and maritime pine, but also of a group of native species of great value.

The spontaneous vegetation of the area, little altered by human activity, constitutes a residual mark of the climatic vegetation of the center of the country, currently covered mainly by eucalyptus, pine forests, and scrub. This spontaneous forest, now circumscribed, is characterized by a dense tree layer dominated by *Prunus lusitanica*, *Castanea sativa*, *Viburnum tinus*, and *Arbutus unedo*. The floristic list of the site includes more than 200 vascular plants species, which corresponds to about a quarter of the total species identified in the region of Serra da Estrela, on an area that represents only 0.02% of the protected area. Among the all the species, *Prunus lusitanica* stands out because it is considered a relic of the Laurisilva type forests, which had high importance in Iberian Peninsula during the Tertiary period.

However, this event was not a unique case, since it has been repeated over time, as can be seen in the following figures where the burned areas over the period between 1990 and 2018 are presented. As can be seen in Figure 6, there is a high frequency in the occurrence of rural fires, indicated on more than 50% of the area of the geological map 1:50,000 (20B—Covilhã), which served as the basis for the projection of all burned areas over the past 28 years. The data were obtained through the website of the National Geographic Information System (https://snig.dgterritorio.gov.pt/), and were superimposed on the geological map 1:50,000 20-B (Covilhã) using WMS files with QGIS 3.6 open-source software, available through the website https://www.qgis.org/en/site/.

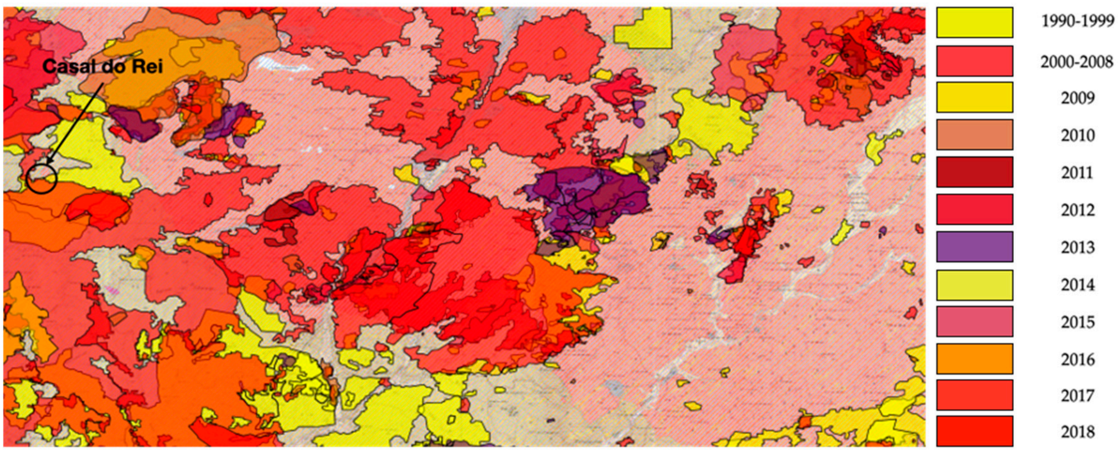

Figure 6. Overlapping of the burnt areas over the period between 1990 and 2018.

In the particular case of the area between the villages of Cabeça and Casal do Rei, it can be seen that rural fires occurred in the period between 1990 and 1999, with the other situation occurring in the period between 2000 and 2008, more precisely in 2005, as previously mentioned. The area has not been struck again by rural fires since then, probably because the occurrences were close in time; a less intense fire occurred two years earlier on June 24, 2003 and consumed much of the vegetation on the slopes of the embedded valley where the Loriga stream runs, as reported in the online version of the newspaper Correio da Manhã.

This redundant occurrence of rural fires in the Serra da Estrela Natural Park led to a gradual destruction of the native forest, much of which is very difficult to recover. That is the case for the continental Laurisilva forest, where the development of small sanctuaries was resumed at great cost, while the rest of the territory is at the mercy of spontaneous and disorderly growth of maritime pines and eucalyptus, or even to a set of invasive species such as acacias, hakeas, or ailanthus.

In the case of acacias, the *Acacia dealbata* species stands out because it is the one that progresses the most in the area, already forming extensive patches, and appears to occupy all types of soils and habitats, including rising in elevation to areas not normally occupied by this type of species. In any case, as can be seen in Figure 7, *Acacia dealbata* already occupies significant areas on land adjacent to the target area of this study, which, despite everything, is not yet in a situation as critical as the one shown in the example presented in following figure.

Figure 7. *Acacia dealbata* groves. As can be seen in the figure on the right, in the Santo António do Alva region, located close to Casal do Rei and also greatly affected by rural fires, one can see a significant dispersion of *Acacia dealbata* groves, which are replacing eucalyptus and maritime pine areas. These acacia groves are easily identifiable through their shade of green, distinct from other species found in the region.

In fact, this species proliferated extensively on the slopes of the mountain, with particular emphasis on the area under analysis in the present work, forcing frequent control actions. These control actions aim to reduce the fuel load present in the forest and try to eradicate this invasive species, which is gaining more and more ground, especially after the occurrence of rural fires. Figure 8 shows the work done in one of these control actions.

In this control action, several methods were used for the control of *Acacia dealbata*, namely cutting and subsequent application of glyphosate, which is a systemic broad-spectrum herbicide that has shown some effectiveness with this species. However, this chemical product also presents environmental and contamination problems, so its use is being avoided on a large scale. For this reason, the use of techniques that are less aggressive to the environment, such as peeling, has been an alternative that shows interesting success rates, despite the time of performance being quite long.

Figure 8. Cutting work and application of control techniques for invasive species. (**a**) Cutting; (**b**) peeling the acacias; and (**c**) application of glyphosate.

During the same procedure, slices were cut from the base of the tree trunks, so that their age could be determined by counting the growth rings. From this, it was possible to verify that the oldest trees corresponded to the period following the fires that occurred in the 1990–1998 interval. It was noted that there is a hiatus in the occurrence of trees, in addition to a few specimens precisely from the period immediately after the last fire in 1998, that only reappeared after 2005—that is, the fire that occurred in 1998 eliminated the cover of pine, eucalyptus, and other native hardwoods, leaving space for the growth of acacias, which once again had an open path by another fire in 2005, which was the last one to hit the area under study, although others have occurred in the vicinity.

5. Conclusions

The Casal do Rei region, located in the Serra da Estrela Natural Park, presents a problem common to many other regions of the country due to the proliferation of invasive species such as *Acacia dealbata*, which already stands out for its large number of occurrences and area, and also other species such as *Acacia melanoxylon*, *Acacia longifolia*, and *Hackea sericea*. The development of the region's forest cover, which developed over thousands of years as a result of successive adaptations to the climate and its transformations, gave rise to a set of habitats occupied by native species, among which are the so-called "*Laurus nobilis* arborescent forests", which is a priority habitat for conservation (5230×pt2) recognized by the European Community through the Habitats Directive (92/43/EEC). Despite successive changes in the typology of vegetation cover, observed mainly throughout the 20th century with the intensive planting of species such as *Pinus pinaster*, and more recently of *Eucalyptus globulus*, extensive patches of species of the genus *Quercus* continued to persist, but also patches of other species that were on the edge of water courses or in niches in more protected areas.

Currently, especially with the increasingly frequent occurrence of rural fires that have swept over almost the entire area of the Natural Park in the last 30 years, the destruction of the native or traditional forest cover has given rise to the emergence in force of invasive species, which are slowly occupying the territory, replacing the remaining species. Thus, there is a marked decrease in biodiversity, while, due to the large amount of dense biomass that these species are able to develop, the risk of occurrence of rural fires increases. This situation creates a cycle of species selection by fire, since the new fires open space for these species, specifically, heliophiles and pyrophytes, to take advantage of every opportunity to conquer new spaces.

Control programs for invasive species are fundamental for the maintenance of ecosystems, and all methods are valid to achieve this. However, given the increasing number of invasive species, as well as the area occupied, it is urgent to develop integrated plans for eradication/control in order to avoid dispersion to areas not yet reached through the creation of rigid and intensive protocols in order to create permanent pressure on the populations of invasive species to reduce their vigor and dispersion capacity.

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CHAPTER 3 – Spread of Invasive Species

Chapter Index

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Article

Allometric, Growth and Biomass Estimation Models for *Acacia dealbata* Link.: a Case Study in Serra da Estrela Natural Park (Portugal)

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Abstract: The use of allometric, growth, and biomass estimation models for the quantification of missing parameters in trees are widely used to estimate the productivity of a stand. However, regarding species with lower economic interest, or exotic invasive species, the creation of these tools did not occur in the same way as for other species, lacking the development of relationships to allow a deeper study of these species. Thus, data were collected in a settlement of *Acacia dealbata* Link. in Portugal, in an area known for the current infestation by this species. After a bibliographic review, some of the identified models were tested to select those who best suit the characteristics of this stand, which were used to develop relationships that, based on the data collected, would be able to estimate parameters that are missing, such as height, volume, or mass, based on measured parameters, such diameter at breast height and height. It was found that the models established, at least for the initial 20 years of the life of the trees, followed a linear model. However, the model still presents some weaknesses. For being considered an invasive species in Portugal, *Acacia dealbata* is frequently controlled and for this reason it is very difficult to find trees older than 20 years.

Keywords: *Acacia dealbata* Link.; allometric models; growth models; biomass estimation models; invasive species.

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1. Introduction

Acacia dealbata Link. is one of the most aggressive invasive tree species worldwide [1]. This species takes advantage of disturbances occurring in ecosystems, competing very effectively with native and other exotic species [2]. For this reason, knowing the parameters that conditioned the dispersion of this invasive species is essential to define the best strategies to its control and eradication [3]. However, despite the existence of studies carried out on growth models, allometric models, or biomass estimation models for many species, very few references addressed the topic for *A. dealbata* [4].

Ecosystems, as described by Levin, are prototypical examples of complex adaptive systems, where patterns at higher levels emerge from localized interactions and selection processes acting at lower levels, which can be verified through the nonlinearity of these systems [5]. This nonlinearity leads to the analysis of historical data and the multiple possible outcomes of its dynamics. Modeling biological parameters presented difficulties since ever, precisely caused by the nonlinearity of the processes involved, and by the variables influencing these processes, which also present high correlation factors among them [6]. The processes associated with forest ecosystems, similar to other terrestrial ecosystems, are complex and multivariate, and aroused the interest of researchers regarding the development of representative models of the reality of the system [7]. Firstly, because they enable an understanding of the development of relationships and processes occurring within and outside of the forest ecosystem [8]. Secondly, the interest in developing models is to predict, for example, the productivity of a forest supplying raw materials or services [9]. For this reason, Landsberg pointed out the need for the models to combine the predictive capacity and flexibility of process-based models, with the empirical information and descriptive accuracy of conventional measurement-based models [10]. However, as mentioned by Bataglia and Sands, the incorporation of process-based forest productivity models into forest management systems is not easy. There is an awareness that the use of more detailed process-based models can play an important role in validating simpler models, in the development of generalizations applicable over long time scales, and for testing hypotheses about how trees react to stresses and external interactions [11].

Models relating parameters such as diameter and height were widely used to describe the growth of trees and development of stands of diverse species. However, regarding *A. dealbata*, available bibliography majorly addresses the perspective of territorial dispersion and its direct competition with native species, focusing on territories where *A. dealbata* is considered an exotic and invasive species, as is the case of Portugal. One example was presented by Raposo et al., where the authors presented a mathematical model to quantify the invasiveness rate of the species [12]. However, perhaps the first reference concerning regression equations that can be used as non-destructive methods to calculate total tree dry weight are the equations presented by Senalwa and Sims [13]. As the authors pointed out, these equations were developed for five eucalyptus species, but they may be suitable to other tree species, such as *Pinus radiata* D. Don or *A. dealbata*. Additionally, Medhurst et al. made a similar assumption, associating *A. dealbata* with *E. nitens* [14]. More recently, Ríos-Saucedo et al. presented allometric models for estimating aboveground biomass in tree sprouts of dendroenergetic crops, including *A. dealbata* [15]. The authors obtained a very accurate prediction of aboveground biomass sprouts. These results were obtained in planted stands for bioenergy, with all trees having similar ages, and with the allometric parameters showing little variability. Thus, the development of a specific model for *A. dealbata*, capable of evaluating stands composed of diverse and heterogeneous specimens, can be very useful.

Modeling the growth rate of a given species allows testing hypotheses and to carry out virtual experiments that could otherwise take years in natural field conditions [16]. The results obtained by Fourcaud et al. allowed the visualization of growth simulations to directly see the outcome of a given model in the current scenario of climate change [17]. The dispersion of invasive species benefits from intense and frequent disturbances to increase dispersal capacity since they are more resilient than native species, which are less agile reacting to new conditions [18]. Knowing growth evolution on a tree or stand level allows well-founded decisions regarding which forest management models should be implemented, concerning strategies to control and eradicate invasive species such as *A. dealbata* [19]. Thus, the objective of this work is to present growth, allometric and biomass estimation models for the species *A. dealbata* based on sampling carried out in a stand located in Portugal.

2. Materials and methods

2.1. Location of the sampling area

To carry out this study, the União de Freguesias de Cabeça e Vide (Seia, Portugal) territory was selected, since there is available abundant biogeophysical information on this location, and where all *A. dealbata* stands were identified and delimited [12,20-23].

Figure 1 shows the location of the sampling area, and Figure 2 shows the sampling and measurements operations on site.

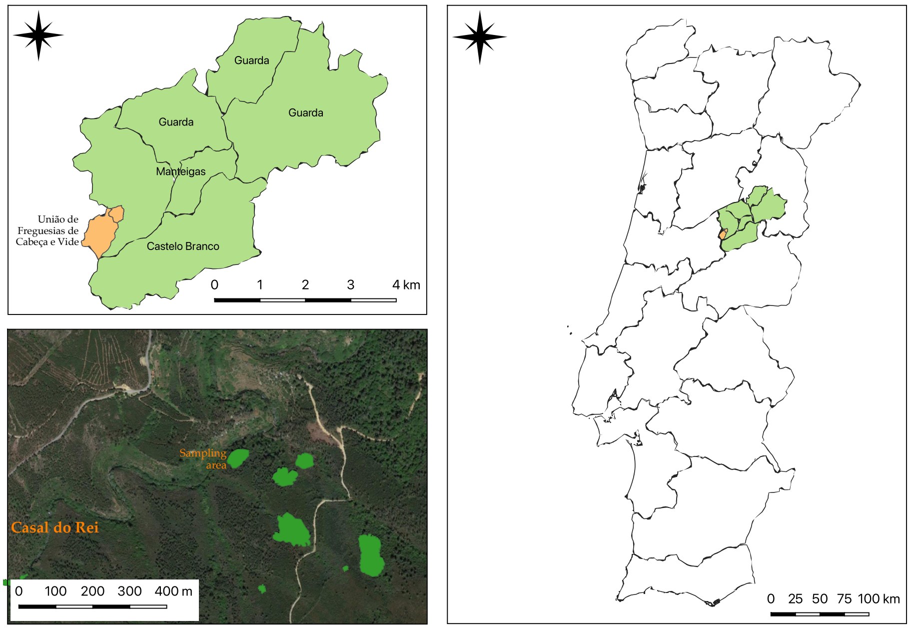

Figure 1. Location of the study and sampling area.

Figure 2. Collection of samples on site. (a) Cutting of trees; (b) separation of the different parts (trunk and branches/foliage); (c) weighing the different parts.

In the stand were marked two circles with a radius of 15 m (approximately 710 m^2 each), resulting in 82 trees of three species (one specimen of *Pinus pinaster*, two specimens of *Arbutus unedo* and 79 specimens of *A. dealbata*). The specimens of *A. unedo* and *P. pinaster* were excluded from this analysis. From the 79 specimens of *A. dealbata*, 20 were selected and completely measured. In the remaining 59 trees only DBHs were measured. For all trees was registered its position in the circles, as presented in Figure 3 and in Table I of the Supplementary Materials. A similar procedure was presented by Peng et al., who applied the generated model in specimens belonging to the same population [24].

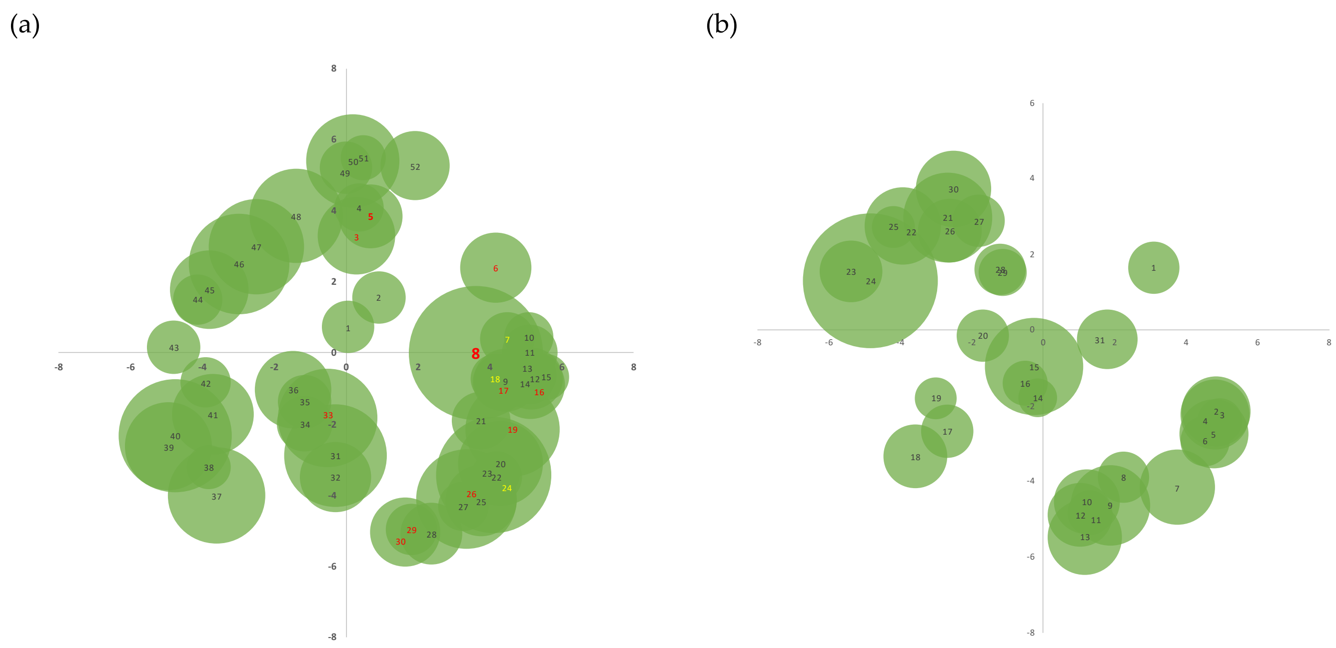

Figure 3. Distribution of the trees in the areas defined to select and collect the samples.

2.2. Model selection

2.2.1. Allometric models

The allometric function is the relation between the height of the tree and the diameter at breast height (DBH) [25]. The importance of this relationship is greater when there is a need to find expeditious methods for determining the height of trees in situations where obtaining this parameter becomes difficult [26]. The determination of hypsometric curves, which are usually established for a particular species and for a particular location, result from the combination of pairs of values, (d; h), which are obtained from a sample population, and that can later be used in the determination of the volume of trees of a given species, and for which only the DBH is known [27,28]. Depending on the species, the height–diameter relationship may follow a sigmoidal-type of evolution, with an inflection point occurring at the end of the data projection.

Despite the extensive research carried out on the establishment of allometric models for many species, there are no known models applied to *A. dealbata*, which is a species with potential for applications as energy crop, or, depending on the region where it is found, can be considered an invasive species needing frequent control actions. The estimation of *A. dealbata* growth allows, in the case of its use and exploitation as a short rotation coppice for bioenergy, the optimization of the associated logistics and a better scheduling of the management operations. Regarding the case when a species presents an invasive behavior, predicting its growth is very important, as it allows to estimate the evolution of the populations, and their impacts on ecosystems. Moreover, by estimating the quantities of biomass, it may potentiate the creation of value chains to enhance the sustainability of the control and eradication actions.

Pretzsch stated that the biological variability observed in ecosystems makes difficult to establish strict functional laws, as happens with physical and mathematics processes, since in the case of biological systems stochastic relationships are more appliable [29]. The establishment of growth relationships, at both the tree and stand levels, together with the biological variability, are of great interest for the analysis of forest growth. Levin et al. stated that the prediction and understanding of the mechanisms beyond the evolution of ecosystems can be based on observed patterns, since those present a unique behavior in any dimension or scale, and will always have their origin in unique causes, leading to unique biological consequences [30]. The authors concluded that the observation of biological phenomena lead to the study of how patterns change, showing a certain variability depending on the scale of description, which influences the development of laws for simplification, aggregation, and scaling. The models were chosen among those described by Schmidt, Lappi, Peng et al. and Pretzsch (Table 1) [24,29,31,32].

Table 1. Selected height–diameter relationships.

Model	Equation	
Assmann (1943)	$h = a + b \times d + c \times d^2$	(1)
Prodan (1951)	$h = 1.3 + \frac{d^2}{a + b \times d + c \times d^2}$	(2)
Petterson (1955)	$h = 1.3 + \left(\frac{d}{a + b \times d}\right)^3$	(3)
Korsun (1935)	$h = e^{[a + b \times \ln(d) + c \times (\ln(d))^2]}$	(4)
Logaritmic	$h = \mathrm{a} + \mathrm{b} \times \ln d$	(5)
Freeze (1964)	$h = e^{[a + b \times \ln d + c \times d]}$	(6)
Loetsch et al. (1973)	$h = 1.3 + \left(\frac{d}{a + b \times d}\right)^2$	(7)

2.2.2. Growth models

As stated by Dale et al., tree growth models project the growth and development of forest ecosystems by increasing the size of each tree used in the simulation, for an annual period, or other periods, depending on the objective [33]. These models express changes in size, both of individual trees and on the forest itself, and represent the evolution of the diameter (d) and height (h), the dependent variables, as a function of time (t), and can be described by a sigmoidal or concave curve. Depending on the species, this curve can be more or less accentuated, since species such as *A. dealbata* show a very rapid growth at the beginning of its life, to reach direct access to sunlight as quickly as possible. Thus, in the initial phase, growth tends to be markedly close to a straight line [34]. Zeide, Burkhart and Tomé presented a list of growth equations (Table 2) [35,36]. As can be seen, most of the equations present a set of parameters equal to or greater than three. As stated by Zeide, the flexibility of an equation depends on the number of parameters [35]. However, Richard Woollons, in a personal communication referred by Zeide, states that there are not significant differences between having two or three parameters for fitting the models [35]. Thus, were selected equations that use fewer parameters.

Table 2. Growth equations.

Model	Equation	
Schumacher	$y = A \times e^{-\frac{k}{t}}$	(8)
Johnson–Schumacher	$y = A \times e^{-\frac{k}{t+b}}$	(9)
Lundqvist–Korf	$y = A \times e^{-k \times \frac{1}{t^n}}$	(10)
Monomolecular	$y = A \times (1 - c \times e^{-k \times t})$	(11)
Logistic	$y = \frac{A}{1 + c \times e^{-k \times t}}$	(12)
Gompertz	$y = A \times e^{-c \times e^{-k \times t}}$	(13)
Sloboda	$y = A \times e^{-c \times e^{-k \times t^b}}$	(14)
Hossfeld IV	$y = \frac{t^k}{c + \frac{t^k}{A}}$	(15)
Richards	$y = A \times (1 - c \times e^{-k \times t})^{\frac{1}{1-m}}$	(16)
Chapman–Richards	$y = A \times (1 - e^{-k \times t})^c$	(17)

Bertalanffy	$y = A \times (1 - e^{-k \times t})^3$	(18)
Weibull	$y = A \times \left(1 - e^{-k \times t^b}\right)$	(19)
Levakovic I	$y = A \times \left(\frac{t^k}{c_1 + t^k}\right)^{c_2}$	(20)
Levakovic II	$y = A \times \left(\frac{t^2}{c_1 + t^2}\right)^{c_2}$	(21)
Korf (or Bailey and Clutter)	$y = A \times e^{-k \times t^{-c}}$	(22)
Yoshida I	$y = A \times \frac{t^k}{c_1 + t^k} + c_2$	(23)

2.2.3. Biomass estimation

Allometric models characterize the causality of deterministic size relations in and between organisms [37,38]. The principle of similarity, extrapolated by Galileo Galilei from the realm of physics to the study of the form and function of plants, was used to establish the allometric models for the length, volume and quantity of biomass by several authors, as presented in Equation 24 [37,39], and that can be rewritten as presented in Equation 25.

$$y = a \times x^b \quad (24)$$

$$w_{biomass} = h \times d^a \quad (25)$$

where $w_{biomass}$ is the biomass weight produced by a tree with total height *h* and diameter at breast height *d*, and *a* corresponds to the allometric exponent.

3. Results and discussion

3.1. Tree height–diameter relationships

The data collected (see Table II of Supplementary Materials) were analyzed using Microsoft ® Excel version 16.54, and IBM ® SPSS Statistics version 27.0.1.0 (64-bit edition). The results are presented in Table 3.

Table 3. Results of the numerical interactions.

Equations	Parameter	Estimate	Std. Error	95% Confidence Interval		R^2
				Lower Bound	Upper Bound	
Assmann (1943)	*a*	4.037	3.276	-2.874	10.948	0.641
	b	1.741	0.490	0.707	2.776	
	c	-0.036	0.015	-0.069	-0.003	
Prodan (1951)	*a*	1.200	1.396	-1.744	4.145	0.648
	b	0.059	0.285	-0.544	0.661	
	c	0.039	0.012	0.014	0.065	
Petterson (1955)	*a*	0.674	0.146	0.367	0.981	0.643
	b	0.321	0.012	0.295	0.348	
Korsun (1935)	*a*	0.427	1.004	-1.691	2.545	0.647
	b	1.647	0.822	-0.087	3.381	
	c	-0.245	0.164	-0.591	0.101	
Logaritmic	*a*	-1.499	3.685	-9.240	6.242	0.630
	b	8.411	1.520	5.218	11.605	
Freeze (1964)	*a*	1.186	0.532	0.064	2.308	0.645
	b	0.901	0.336	0.191	1.610	
	c	-0.035	0.025	-0.087	0.016	
Loetsch et al. (1973)	*a*	0.595	0.048	0.493	0.696	0.640
	b	0.018	0.003	0.011	0.024	

The projection of the estimated values around the expected normal, the projection of the deviation of the estimated values from the normal, and the error of the estimated values is presented in Figure I of the Supplementary Materials. Figure II of the Supplementary Materials presents the projections of the predicted values and corresponding residuals to check homoscedasticity. The coefficients generated in the nonlinear regression are presented in Table 4.

Table 4. Equations generated based on the coefficients shown in Table 3.

Model	Equation	
Assmann (1943)	$h = 4.037 + 1.741 \times d - 0.036 \times d^2$	(26)
Prodan (1951)	$h = 1.3 + \frac{d^2}{1.2 + 0.059 \times d + 0.039 \times d^2}$	(27)
Petterson (1955)	$h = 1.3 + \left(\frac{d}{0.674 + 0.321 \times d}\right)^3$	(28)
Korsun (1935)	$h = e^{[0.427+1.647\times\ln(d)-0.245\times(\ln(d))^2]}$	(29)
Logarithmic	$h = 1.0 - 0.971 \times \ln d$	(30)
Freeze (1964)	$h = e^{[1.186+0.901\times\ln d-0.035\times d]}$	(31)
Loetsch et al. (1973)	$h = 1.3 + \left(\frac{d}{0.595 + 0.180 \times d}\right)^2$	(32)

Note: *d* is the diameter at breast height (DBH); *e* is the Euler number (approximately 2.7183); *h* is the height of the tree.

It was found that five of the seven equations have coefficients with lower and upper bounds presenting negative and positive results simultaneously. This allow to conclude that in these situations the value zero can be chosen. So, these coefficients are considered as being statistically non-significant. Thus, the equations from Assmann (1943), Prodan (1951), Korsan (1935), Logarithmic and Freeze (1973) are excluded, since they present coefficients that are statistically non-significant. On the other hand, in the equations presented by Petterson (1955) and Loetsch et al. (1973), the coefficients have lower and upper bounds, both negative or both positive, for a confidence interval of 95%, indicating that do not include the zero in any situation. For this reason, the coefficients obtained from the models by Petterson (1955) and Loetsch et al. (1973) can be considered statistically significant. Regarding standard errors, these two models also present significant differences compared to the others, as they present standard errors that are lower than those for the other equations. In fact, the equation by Petterson (1955) has a value of 0.146 for the standard error of coefficient *a*, and 0.012 for the standard error of coefficient *b*, whereas the equation presented by Loetsch et al. (1973) presents a value of 0.048 for the standard error of coefficient *a*, and 0.003 for the standard error of coefficient *b*. The R^2 values for the seven models presented values between 0.630 for the Logarithmic model, and 0.648 for the Prodan model (1951). These R^2 values mean that the models explain 63.0% and 64.8% of the total variation in tree height, respectively. The Assmann (1943), Prodan (1951), Korsun (1935), logarithmic and Freeze (1964) models, despite presenting interesting R^2 values, with even the model of Prodan (1951) presenting the value of a higher R^2 at 0.648, should not be considered for the reasons mentioned above. Thus, the values of R^2 for the model of Petterson (1955), which was 0.643, means that this model explains 64.3% of the total variation of tree height, whereas the model by Loetsch et al. (1973), which presented an R^2 value of 0.640, means that this model explains 64.0% of the total variation in tree height. Regarding homoscedasticity, all models presented a good dispersion of data, constituted by the standardized predicted values and the standardized residual values. However, there is a slight asymmetry, as all models have a distribution of standardized residual values mostly below the origin line. Concretely, of the 20 projected values, 12 are below this line, whereas 8 are above it. This distribution points to a slight asymmetry of the models. The models can be considered as being well-adjusted, as all, without exception, present the residuals randomly dispersed around zero, showing a constant variance, with the data obtained by measurement concentrated between -2 and 2.

3.2. Tree growth models

The cut samples were weighed and measured. After, were sliced every 50 cm, and growth rings counted and the annual increment measured, as shown in Table III of the Supplementary Materials and in Figure 4.

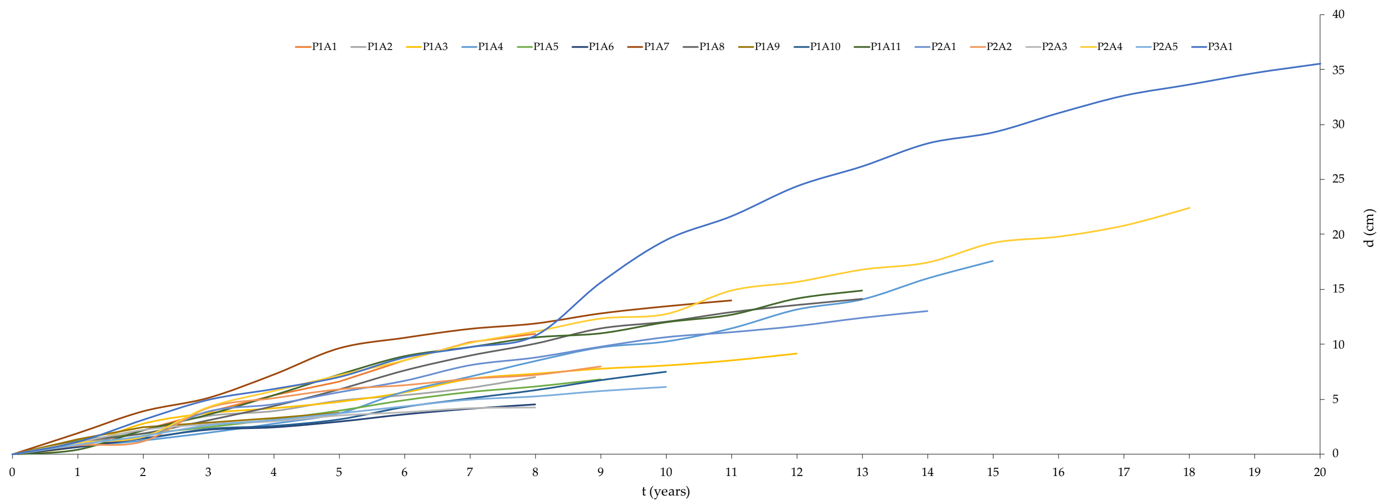

Figure 4. Relationship d = f(t) for the trees used in the study.

As can be seen, the trees present a fast initial growth rate, which is confirmed by the linearity of the increase in diameter. Subsequently, to increase the available data were converted into cumulative data corresponding to each of the growth years, as presented in Table IV of the Supplementary Materials. These data were used in the numerical iterations to determine the parameters of the Schumacher and Bertalanffy equations. This data configuration allowed to transform the 17 initial samples into 191, giving greater significance to the results, from a statistical point of view. Then, the models were used to estimate the parameters for the Schumacher and Bertalanffy equations (Table 5).

Table 5. Results from the numerical interactions using the software IBM ® SPSS Statistics.

Model	Parameter	Estimate	Std. Error	95% Confidence Interval		R^2
				Lower Bound	Upper Bound	
Schumacher	*a*	13.778	0.276	13.233	14.324	0.967
	k	10.454	0.204	10.051	10.858	
Bertalanffy	*a*	9.331	0.170	8.995	9.667	0.971
	k	0.162	0.003	0.156	0.167	

With the data presented in Table IV of the Supplementary Materials and the parameters presented in Table 6 it was possible to formulate the equations shown in Table 6. In a first analysis and looking only at the parameter *a* referring to the asymptote, the Schumacher equation presents a value of 13.778, which corresponds to the maximum height from which tree growth stops, although tree development continues, for example, increasing trunk diameter. This value, about 3.5 meters higher than what is presented for the equation formulated using the model proposed by Bertalanffy, seems to be more in line with the values observed in the measurements performed, as all observed values are above this value, except for two of the measured trees.

Table 6. Equations generated based on the coefficients shown in Table 5.

Model	Equation	
Schumacher	$h = 13.778 \times e^{-\frac{10.454}{t}}$	(33)
Bertalanffy	$h = 9.331 \times (1 - e^{-0.162 \times t})^3$	(34)

The obtained R^2 values indicate that the calculated parameters influence 96.7% and 97.1% the determination of the height, respectively, for the Scumacher anad Bertalaffy equations.

3.3. Biomass weight estimation

Table 7 presents the results obtained using Equation 26.

Table 7. Results obtained in the numerical interactions.

Parameter	Estimate	Std. Error	95% Confidence Interval		R^2
			Lower Bound	Upper Bound	
a	0.823	0.035	0.749	0.897	0.754

The allometric exponent *a* presented a value of 0.823, with a standard error of 0.035, framed in a lower bound of 0.749 and in an upper bound of 0.897, with an R^2 of 0.754. The predicted results obtained showed a mean value of 157.86 kg, with a standard error of 28.60, with a lower bound of 96.89 and an upper bound of 218.82, for a 95% confidence interval. The calculated standard deviation was 114.40. The minimum value verified was 33.83, and the maximum value was 413.15. Based on the coefficients generated in the non-linear regression iterations for the model selected, it was possible to build the equation presented in Table 8.

Table 8. Equation generated based on the coefficient shown in Table 8.

Model	Equation	
Biomass estimation model	$w_{biomass} = a \times d^{0.823}$	(35)

The Q–Q normal plot of predicted values is presented in Figure 5(a). Figure 5(b) shows the projection of the standardized predicted values and the standardized residual values.

(a) (b)

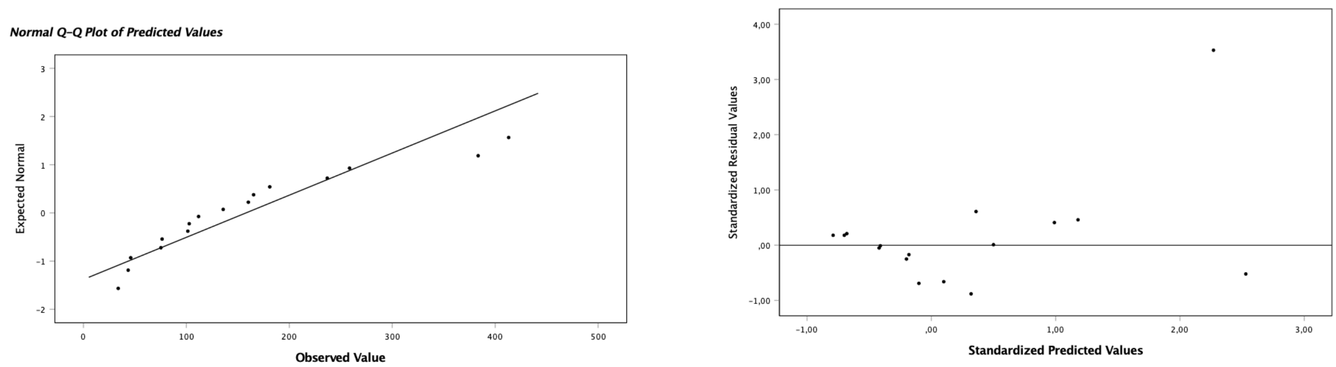

Figure 5. (a) Normal Q–Q plot of the predicted values; and (b) standardized predicted values and standardized residual values.

As can be seen in Figure 5(a), the observed values are arranged in a very regular way along the line that represents the expected normal, indicating a tendency to overlap the line and a reduced variance. This tendency to overlap should be greater with a greater number of data, but with the number of data currently available, it is already possible to verify a good fit of the model. On the other hand, in the graph shown in Figure 5(b), from the projection of the standardized predicted values and the standardized residual values, the values are found to be between -2 and 2, with only 2 points to be placed in the interval between 2 and 3. This distribution indicates a good fit of the model.

4. Performance analysis of the models

4.1. Height–diameter relationship

For the performance analysis of the models, Petterson (1955) and Loetsch et al. (1973) equations were applied to the DBH data collected by direct measurement from the 59 trees that were part of the two transepts delimited in the study area, and which were not used in the construction of the mathematical models. The results of applying the two equations are presented in Table V of the Supplementary Materials. The normality of the results was evaluated as shown in Figure 6.

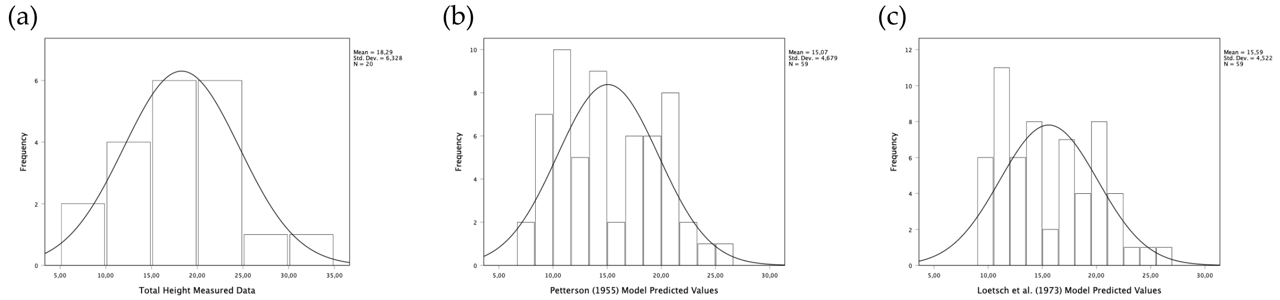

Figure 6. Histograms corresponding to the distribution of data (a) obtained by directly measuring the trees used in the construction of the models; (b) obtained by applying the model of Petterson (1955); and (c) obtained by applying the model by Loetsch et al. (1973).

As can be seen from the analysis of the histogram shown in Figure 6(a), the data tend towards the normal distribution, as shown by the application of the Kolmogorov–Smirnov test (since $n < 30$), which presented a $p > 0.05$, and validated the H_0 hypothesis for this reason. That is, the results pointed to a normal distribution. On the other hand, in the histograms shown in Figure 6(b) and Figure 6(c), it is possible to observe some deviations from the normal distribution, which are also confirmed with the application of the Shapiro–Wilk test (for $n > 30$) that presented $p < 0.05$ for both situations, leading to the choice of the alternative hypothesis, H_1, which points to the fact that the distribution is not normal. This non-normality of the data obtained by the application of the models may be related to the fact that the sample used for the application of the models, given the scarcity of some of the diameter classes, may affect the type of distribution verified in the data. When analyzing the projection of the observed values and their relationship with the expected normal, which is shown in Figure 7, it is verified that the observed values overlap very well with the expected normal line, except for the values corresponding to the largest diameters. This situation occurs, once again, probably due to the lack of data on these diameter classes, but as mentioned above, it is very difficult to find specimens older than 20 years.

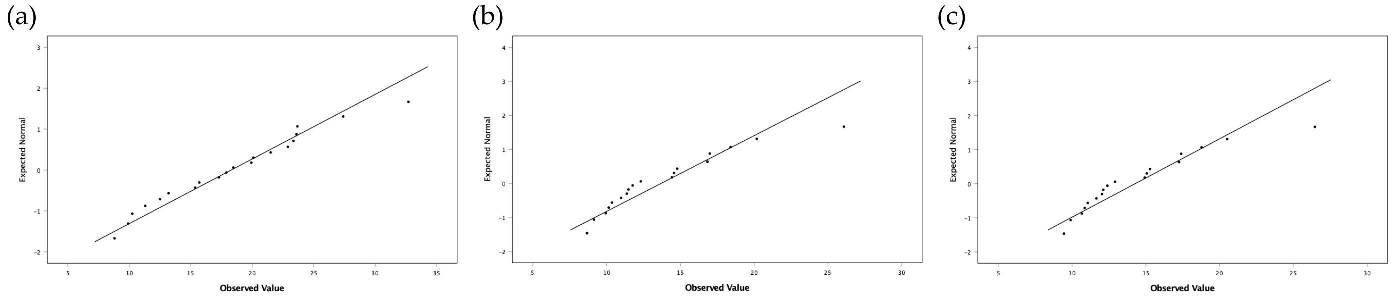

Figure 7. Normal Q–Q plot of (a) the total height of the measured data; (b) Petterson's (1955) predicted value; e (c) Loetsch et al.'s (1973) predicted value.

The comparison of the descriptive parameters is shown in Table 9.

Table 9. Comparison of the descriptive parameters calculated for each of the datasets.

		Total Height Measured Data	Petterson (1955) Predicted Values	Loetsch et al. (1973) Predicted Values
Mean		18.29	13.70	14.27
Standard deviation		6.33	4.49	4.35
n		20	59	59
Confidence interval (95%)	Lower bound	15.33	11.60	12.24
	Upper bound	21.23	15.80	16.31
Variance		40.05	20.16	18.92

From the direct comparison of the data, it appears that those obtained by applying the model generated from Loetsch et al. (1973) is the closest to the parameters obtained by directly measuring the sampled trees used to build the model. As can be seen from the data presented for the total height of the measured data, the variance is much higher than in the other datasets, which is most likely related to the number of samples used, and the type of *A. dealbata* stand used as reference. The variance of the remaining datasets was significantly lower, reaching its minimum value in the dataset referring to the predicted values using Loetsch et al. (1973) equation. This group also presented a smaller standard deviation, as well as a smaller difference between the lower and upper bounds for a confidence interval of 95%, with a value of 4.07, whereas the dataset referring to the predicted values using Petterson (1955) equation presented a value of 4.2. Thus, it is understood that the most adjusted model seems to be the equation created from the model presented by Loetsch et al. (1973):

$$h = 1.3 + \left(\frac{d}{0.595 + 0.180 \times d}\right)^2 \quad (36)$$

This model, despite the good adjustment it presents, must be conditioned in its current use to specimens under the age of 20 and their corresponding DBH, since, in the model generation, it was not possible to use specimens in representative quantity to give significance to these classes of diameters. As *A. dealbata* is considered an invasive species in Portugal, stands are frequently controlled, making it difficult to find trees older than 20 years. In fact, among the 79 trees analyzed, only one specimen was 20 years old at the date the samples were cut (in October 2018), and all the other trees were younger.

The ability of *A. dealbata* to grow very quickly, especially in height, as a way of conquering direct access to the sunlight, seems to be in accordance with the growth represented by a curve with a concave format. On the other hand, species that present slower growth, as shown in the studies by Jackson et al., who analyzed the growth of several species of the genus *Pinus* and the genus *Quercus*, found that in species with faster initial growth, the projection curve of the allometric model followed the concave type, whereas in species with slower growth, the allometric model is best represented by a sigmoidal curve [40]. This relationship can also be better verified the greater the number of specimens in the sample is, and, mainly, the longer the available growth period of the trees is. This is because the existence of very old specimens will allow for confirming whether the growth of the trees has already reached the asymptote and stabilized, as it may be the case that the growth of the trees is in the ascending phase and has not yet reached the inflection point towards stabilization. The relationships between the different elements of a stand can also interfere with growth, both positively and negatively, as mentioned by Enquist and Niklas. As such, organizing principles are needed to link organism, community and ecosystem attributes across spatial and temporal scales [41]. However, the type of very fast growth in the phase immediately after germination seems to be related to, and is more common in, heliophile species, as is the case of *A. dealbata*. However, the development of trees for the first 20 years follows a growth that can be well adjusted to a linear model. In this way, establishing a linear relationship between diameter and height, which is statistically significant, can allow for the quick assessment of one of the most critical characteristics of forest stands, especially when it comes to stands destined to the supply of industrial raw materials. Diameter is one of the properties of trees that determine, for example, their cutting moment or the use of the wood. Equation 39 shows the linear relationship between diameter and height, with $R^2 = 0.807$.

$$d = -1.84 + 2.92 \times h \quad (37)$$

4.2. Growth model

For the validation of the models, the equations were applied to a time sequence of 50 years to verify the evolution of the height of the trees over this period (Figure 8). The data generated with the descriptive statistical parameters presented in Table 10 are very close to the values verified for the height measured in the collected samples, thus indicating a good fit of the model. The results from the Schumacher equation presented a mean value of 3.27, with a standard deviation of 2.28, a lower bound of 2.95, an upper bound of 3.60, and a variance of 5.18. On the other hand, the results from the Bertalanffy equation presented a mean value of 3.26, with a standard deviation of 2.30, a lower bound of 2.93, an upper bound of 3.59, and a variance of 5.30.

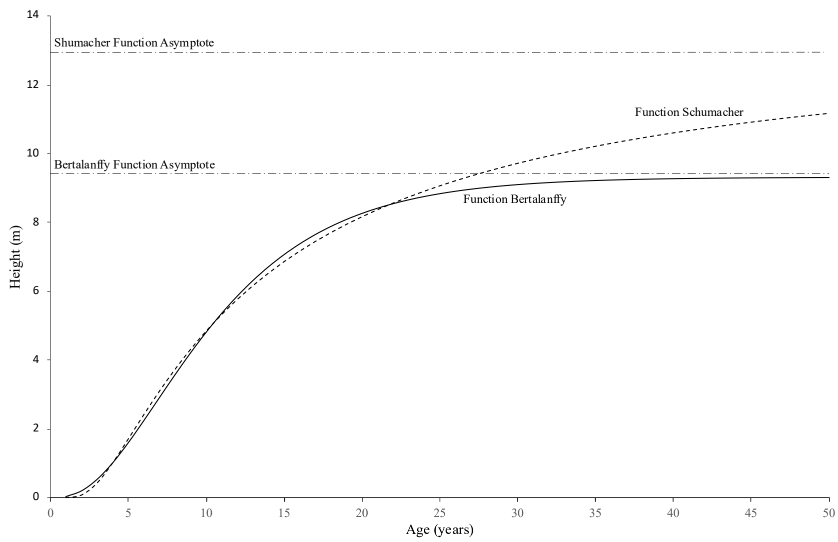

Figure 8. Evolution of height growth models for *A. dealbata* calculated from the Schumacher and the Bertalanffy equations.

Table 10. Comparison of the descriptive parameters calculated for each of the datasets.

		Height Measured Data	Schumacher Predicted Values	Bertalanffy Predicted Values
Mean		3.38	3.27	3.26
Standard deviation		2.15	2.28	2.30
n		191	191	191
Confidence interval (95%)	Lower bound	3.07	2.95	2.93
	Upper bound	3.69	3.60	3.59
Variance		4.62	5.18	5.30

The descriptive statistical parameters presented by the results from the Schumacher equation are closer to the measured height values than the values obtained from the Bertalanffy equation. This observation could, at first sight, suggest a better fit of the Schumacher model compared to the Bertalanffy model. However, from the projection shown in Figure 12, the two models practically overlap in the first 20 years of tree growth, allowing the assumption that both models fit well to the initial growth period. However, it appears that the Schumacher model never reaches the asymptote during the simulation established for the 50-year period, whereas the Bertalanffy model reaches the asymptote and presents a perfect curve. This observation, although based on a relatively small number of data, may indicate a better fit of the Bertallanfy model. However, both models need to be fine-tuned with the inclusion of data obtained from specimens aged over 20 years to confirm the height asymptote.

As mentioned, the available data do not encourage the extrapolation of the results to analyze growth for periods longer than 20 years. However, the two generated models present an acceptable fit for the initial 20 years of the life of *A. dealbata* trees. As can be seen in Figure 9, the initial growth seems to fit, in both cases, to a linear model.

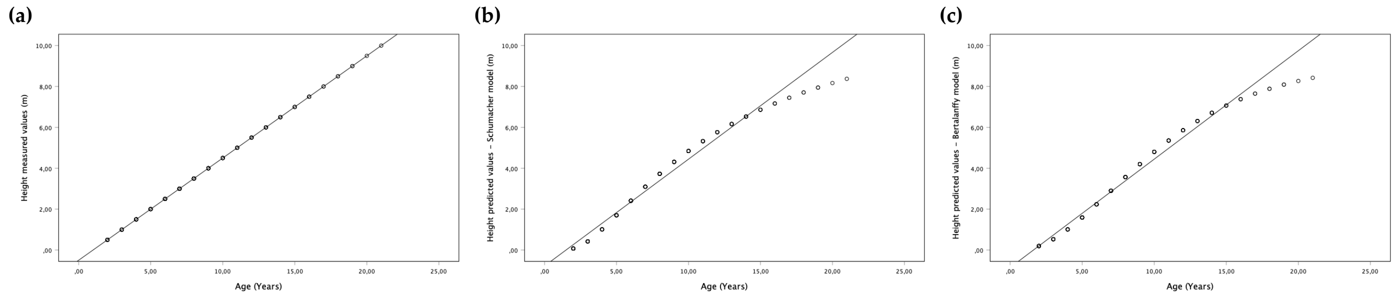

Figure 9. (a) Linear model of the projection of height and age determined for the samples used in the study; (b) linear model of the predicted height projection determined using the Schumacher model; and (c) linear model of the predicted height projection determined using the Bertalanffy model.

The following trend adjustment lines resulted from the projection of the values described by the equations presented in Table 11.

Table 11. Linear models for the height versus age projections for the data obtained by measurement and for the data obtained through the application of the Schumacher and Bertalanffy models.

Equation	Model	R^2	
$h = -0.5 + 0.5 \times t$	Measured data	1.00	(38)
$h = -0.779 + 0.522 \times t$	Data from the Schumacher model	0.974	(39)
$h = -0.858 + 0.530 \times t$	Data from the Bertalanffy model	0.981	(40)

The linear relationships generated from the data obtained using the Schumacher and Bertalanffy models are very close with the linear model generated from the measured values, as can be seen through the values of R^2, which, in the case of the Schumacher model, presenting a value of $R^2 = 0.974$, and for the case of the Bertalanffy model, presents a of $R^2 = 0.981$. These values are both very close to the R^2 presented by the linear model defined by the measured values. In all situations, the normality tests performed (Kolmogorov–Smirnov test) presented $p > 0.05$, indicating that the data follow a normal distribution.

4.3. Biomass estimation

For the validation of the formula generated for the biomass quantification, the biomass quantity was estimated based on the data presented in Table III of Supplementary Materials, namely, the diameter and the height data. Then, with the results obtained, the estimated dataset was compared with the dataset obtained by weighing the samples collected in the area selected for the study. For this comparison, the non-parametric Wilcoxon test was used, which presented $p > 0.05$. Thus, with this result, hypothesis H_0 is accepted. That is, the two sets of data are identical to each other. As the value of Z generated in the Wilcoxon test was negative, it means that the negative ranks predominate over the positive ranks, so it can also be concluded that the estimated values tend to be lower than the real measured values. This fact must be considered when estimating the amount of biomass of *A. dealbata* using this model. However, a linear relationship was also established between the biomass weight of the collected samples and the diameter of these same samples. It was found that the generated trend line (Equation 41), despite being close to most of the projected values with an $R^2 = 0.819$, could be easily improved with the adjustment of a quadratic function (Equation 42), which presented a result of $R^2 = 0.882$, as shown in Figure 10.

$$w = -126 + 20.12 \times d \quad (41)$$
$$w = 1.35 - 0.72 \times d + 0.65 \times d^2 \quad (42)$$

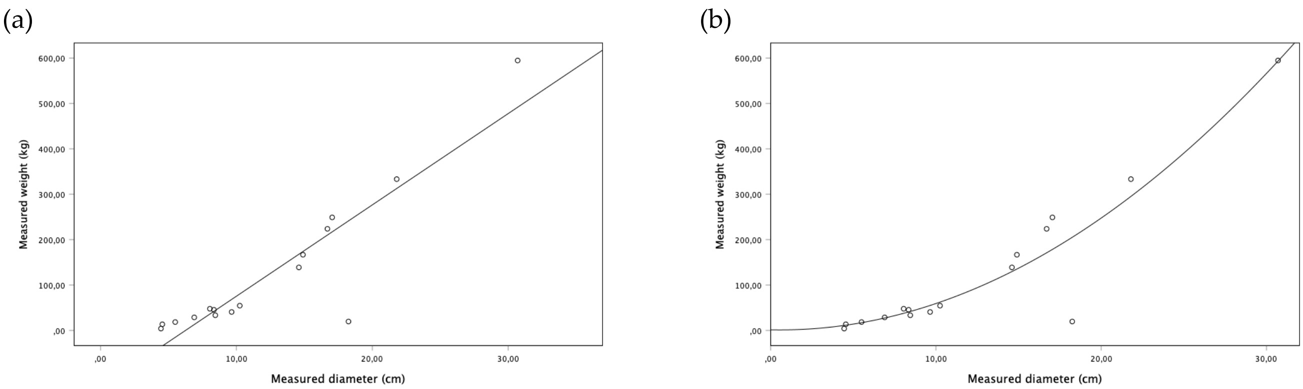

Figure 10. (a) Establishment of a linear relationship between the measured weights of the samples collected and the diameters of these samples; and (b) the establishment of a quadratic-type relationship between the measured weights of the collected samples and the diameters of these same samples.

4.4. Model application

The estimation of biomass is important from the perspective of forest productivity when it comes to species of interest for the supply of raw materials or for bioenergy, but also from a long-term perspective, for example, for estimating the capacity of forest species for carbon capture and sequestration, as a measure to mitigate climate change. The application of the models can be used in the quantification, for example, of income from the sale of wood, whether it is intended to produce sawmill products, or biomass to energy. In places where *A. dealbata* is considered invasive, as is the case of Portugal, the estimation of biomass can be used, firstly, to a better organization of control and eradication actions. On the other hand, estimating the amount of biomass allows a better management of productive planted forests. The use of the simplified linear and quadratic models developed seems to indicate the possibility of a use adjusted to stands or trees under 20 years of age. The use of Equations 37, 40 and 42 sequentially established a relationship for measuring growth rates of the type h = f(t), d = f(h) and w = f(d), allowing for the creation of the abacus shown in Figure 17.

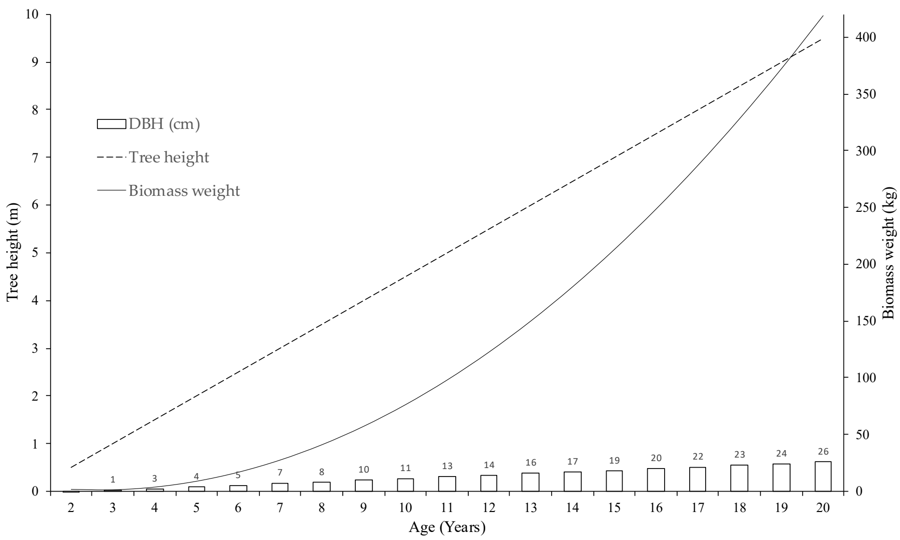

Figure 11. Height, diameter, and biomass weight estimation as a function of time.

The use of a tool, such as the one shown in Figure 17, can allow for the quick determination of missing parameters in field forest surveys, and forest inventory, but also in a perspective of optimizing the control operations of this invasive species in Portugal, for example, by estimating the quantities of biomass available in a certain location, allowing the creation of a value chain through energy recovery.

5. Conclusions

Parametric and allometric models, growth equations, or biomass estimation models can be used to determine the dimensions of trees in a non-destructive way when it is not possible to obtain the desired information otherwise. There are several models available which have already been applied to different species. Regarding species that may acquire an invasive behavior, as is the case of *A. dealbata* in Portugal, models that had been developed specifically for this species are not available, so it is presented as an innovative and necessary development, given the importance that the study of this species presents, particularly due to the need to its control and eradication. In this way, the models selected from the available bibliography were applied to data collected in Portugal. From the application of non-linear methods, equations derived from the selected models were obtained, which were statistically analyzed to assess their significance. This analysis resulted in the selection of the equations that were shown to be the most significant from a statistical point of view, which were then validated by applying them to a set of trees that had been previously measured. From the results obtained, it appears that there is a good fit with the linear models, at least for the development period of the first 20 years of the life of the trees. Thus, as most of the *A. dealbata* stands found in Portugal are younger than 20 years old, the use of linear models seems to be an excellent tool to estimate the growth parameters of this species.

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CHAPTER 4 – Control of Invasive Species

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recycling

Article

Energy Recovery from Invasive Species: Creation of Value Chains to Promote Control and Eradication

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Abstract: The use of biomass as an energy source presents itself as a viable alternative, especially at a time when the mitigation of climate change requires that all possibilities of replacing fossil fuels be used and implemented. The use of residual biomass also appears as a way to include in the renewable energy production system products that came out of it, while allowing the resolution of environmental problems, such as large volumes available, which are not used, but also by the elimination of fuel load that only contributes to the increased risk of rural fires occurrence. Invasive species contribute to a significant part of this fuel load, and its control and eradication require strong investments, so the valorization of these materials can allow the sustainability of the control and eradication processes. However, the chemical composition of some of these species, namely *Acacia dealbata*, *Acacia melanoxylon*, *Eucalyptus globulus*, *Robinia pseudoacacia* and *Hakea sericea*, presents some problems, mainly due to the nitrogen, chlorine and ash contents found, which preclude exclusive use for the production of certified wood pellets. In the case of *Eucalyptus globulus*, the values obtained in the characterization allow the use in mixtures with *Pinus pinaster*, but for the other species, this mixture is not possible. From a perspective of local valorization, the use of materials for domestic applications remains a possibility, creating a circular economy process that guarantees the sustainability of operations to control and eradicate invasive species.

Keywords: invasive forest species; wood pellets; circular economy; sustainability; value chain

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1. Introduction

The use of biomass as an energy source is increasingly presented as a current alternative, in the permanent search for more sustainable forms of energy, which can somehow replace traditional sources of fossil origin, such as oil and coal [1]. However, the use of biomass as an energy source is not a recent application, since this is the oldest energy source that man learned to use, from the moment that they discovered how to control fire for their own benefit, passing this on to be part of daily life situations [2]. Since time immemorial, human populations have started to have in their routine the acquisition of biomass fuels, through their collection and storage, thus being available to supply needs such as space heating, cooking, lighting, and even protection by keeping wild animals away [3].

Currently, biomass remains the most widespread source of energy among the most remote populations, essentially due to its availability and ease of use, giving it the epithet "energy of the poor", since they are usually the most disadvantaged populations, mainly in Africa, Southeast Asia and some regions of Latin America, which this more rudimentary use continues to occur [4]. However, in the more developed countries there is also an increase in the use of biomass as a source of primary energy because of, in addition to the traditional consumption associated with the heating of residential spaces in the form of firewood consumption, the consumption of fuels derived from biomass, such as wood pellets and briquettes, both for heating, but also for more industrial applications, such as the production of industrial steam, and even the production of electric energy [5].

These more industrial uses, however, have led to an increasing standardization of fuel quality criteria in order to optimize their use, defining a set of characteristics, namely its heating value, but also the maximum limits of certain chemical constituents, such as the content of sulfur, chlorine and alkali metals, due to their behavior during combustion, and contribution to the occurrence of corrosive, fouling and slagging phenomena [6,7]. For this reason, the use of biomass is currently very limited to selected types which meet a set of quality requirements, leaving a set of forms of biomass considered to be residual in the supply chains, as are the materials resulting from operations forest management and agricultural activity [8,9].

Within this huge group of residual biomasses resulting from forest management operations, there are numerous tree and shrub species, which, since they have no commercial and/or industrial application, are abandoned on forest land, even after cutting, contributing to the increase in fuel load and consequent increase in the risk of rural fires [10]. Some of these species, in turn, are even exotic species, with invasive behavior, which due to their aggressiveness and competitiveness vis-à-vis native species, are conquering space and replacing native flora, making it possible to identify these situations all over the world [11]. This substitution of native species by invasive species has very negative effects that go far beyond the loss of biodiversity and changes in ecosystems, since they also hinder the development of productive forests by competing directly with the installed species [12].

In Portugal, the phenomenon of the expansion of invasive species has acquired very worrying proportions, mainly with a group of species of the genus *Acacia*, from which the *Acacia dealbata* and the *Acacia melanoxylon* stand out, but also with other species, namely the *Eucalyptus globulus*, the *Robinia pseudoacacia* and *Hakea sericea* [13]. This group of species has progressed almost exponentially, already covering extensive areas. However, the problem is not limited to these species, there are also problematic situations with *Acacia longifolia*, *Cortaderia selloana*, *Arundo donax* and *Ailanthus altissima*, among others, with which different means have been employed in order to try to eradicate, or at least control, the progression of these species [14]. The most serious situation in Portugal is that of the uncontrolled expansion of *Acacia dealbata*. This species has grown in area by more than 400% since the 70s of the 20th century, being currently the invasive species that occupies the largest area in the national territory (Figure 1). However, other species exhibit similar behaviors, making the situation even more serious.

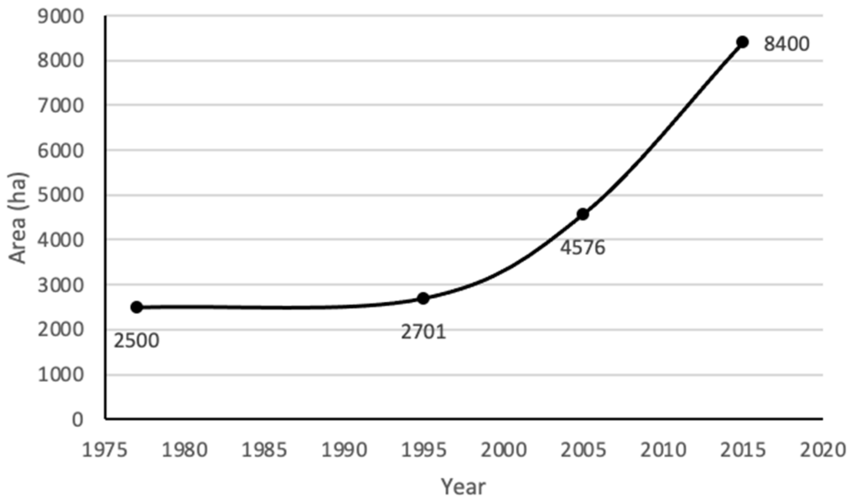

Figure 1. Evolution of the area occupied by *Acacia dealbata* (adapted from [14–16]).

The creation of value chains, with the objective of promoting the use of these species, presents itself as a possibility that allows the balance of the costs generated with the operations of control of the invaders [17]. These value chains, which already exist today, encourage the forwarding of these residual materials to biomass thermoelectric plants, which give them a low financial value, often scarcely enough to pay for the different tasks of forest management, such as cutting, filling and transport, and giving no value to the combustible material, claiming its low density, high moisture content and, mainly, due to the low energy properties that some species have [18]. However, there are some species that may have a good potential for energy recovery, and that, even if they are not used as the sole source of raw material for the production of fuels derived from biomass, can be incorporated with traditional species, namely the *Pinus pinaster*, or other resinous species [19].

This perspective of valorization of residual biomasses, originating from invasive species, can be very helpful in combating, almost always unevenly, the dispersion of these species, contributing to the share of costs with the control and eradication operations [20]. In this way, the creation of these value chains may play a decisive role in the preservation of indigenous biodiversity, while contributing to the reduction in the risk of occurrence of rural fires, since the need to supply valuable raw materials promotes permanent pressure on invasive species, controlling their growth and dispersion, limiting the accumulation of fuel load [21]. In this article, the potential use of these species in the production of wood pellets is discussed, both individually and in mixtures with *Pinus pinaster* wood, in order to justify the creation of value chains that promote pressure on invasive species, ensuring the sustainability of control and eradication operations for these species. The present work has as its main objective the characterization of a set of species, namely, *Acacia dealbata*, *Acacia melanoxylon*, *Robinia pseudoacacia*, *Eucalyptus globulus* and *Hakea sericea*, and their subsequent comparison with the dominant species most used in production of solid fuels derived from biomass, such as wood pellets, which is *Pinus pinaster*.

2. Results

2.1. Thermogravimetric Analysis

The results obtained in the thermogravimetric analysis are shown in Figure 2.

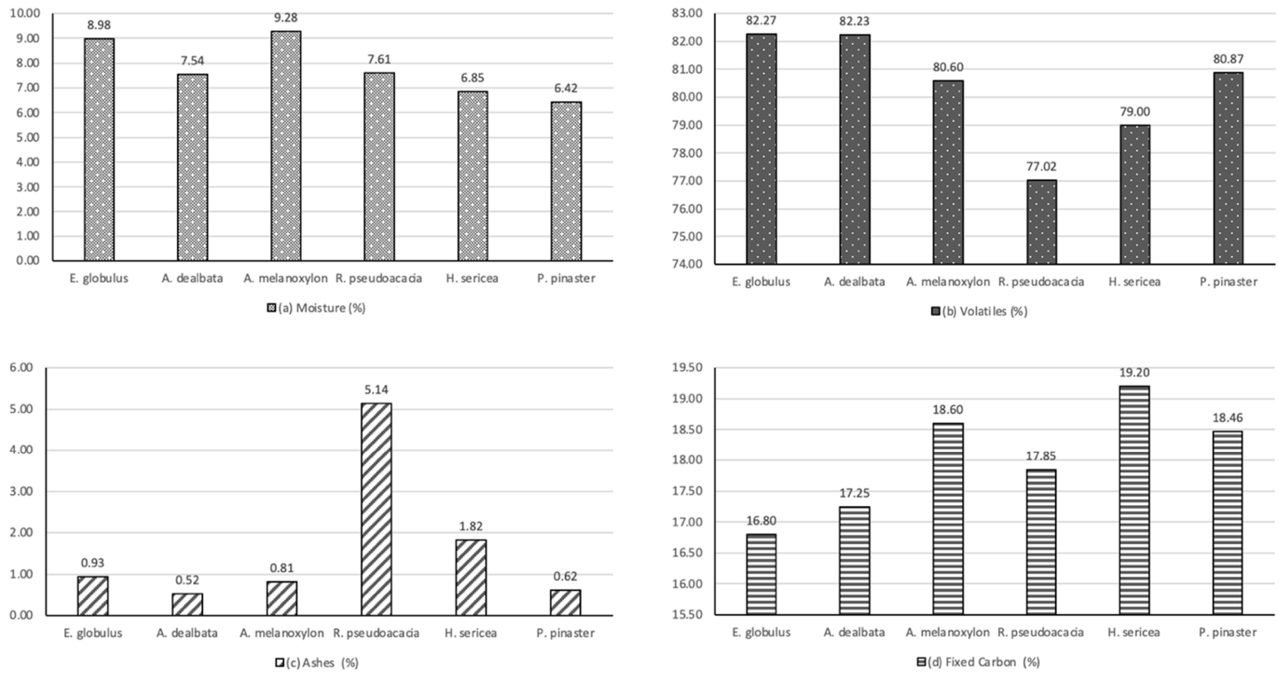

Figure 2. Results of the thermogravimetric analysis.

Moisture is a less important characteristic because it depends directly on the time and type of drying performed. For drying described in Section 2.1. Sampling and preparation, the results varied between 6.42% of *Pinus pinaster* and 9.28% of *Acacia melanoxylon*. The remaining species show very close values, between 6.85% and 8.98%. The volatile content varied between a minimum value of 77.02%, for *Robinia pseudoacacia*, and a maximum value of 82.27%, for *Eucalyptus globulus*. The remaining species varied between 79.00% and 82.23%. The ash content varied between a minimum value of 0.52% for *Acacia dealbata* and a maximum value of 5.14% for *Robinia pseudoacacia*. The remaining species varied between a minimum value of 0.62% and a maximum value of 1.82. The fixed carbon content showed a minimum value of 16.80%, for *Eucalyptus globulus*, and a maximum value of 19.20%, for *Hakea sericea*. The remaining species showed values between 17.25% and 18.60%.

2.2. Elemental Analysis CHNO

The results obtained in the elemental analysis are shown in Figure 3.

The carbon content varied between a minimum value of 47.00% for *Acacia dealbata* and a maximum value of 60.00% for *Hakea sericea*. The remaining species varied between 47.30% and 50.21%. The hydrogen content varied between a minimum value of 5.61%, for *Acacia melanoxylon*, and a maximum value of 6.07%, for *Pinus pinaster*. The remaining species varied between 5.67% and 5.92%. The nitrogen content varied between a minimum value of 0.080%, for *Pinus pinaster*, and a maximum value of 0.711%, for *Hakea sericea*. The remaining species varied between 0.099% and 0.582%. The oxygen content varied between a minimum value of 33.40% for *Hakea sericea* and a maximum value of 47.07% for *Acacia melanoxylon*. The remaining species varied between 43.64% and 46.93%.

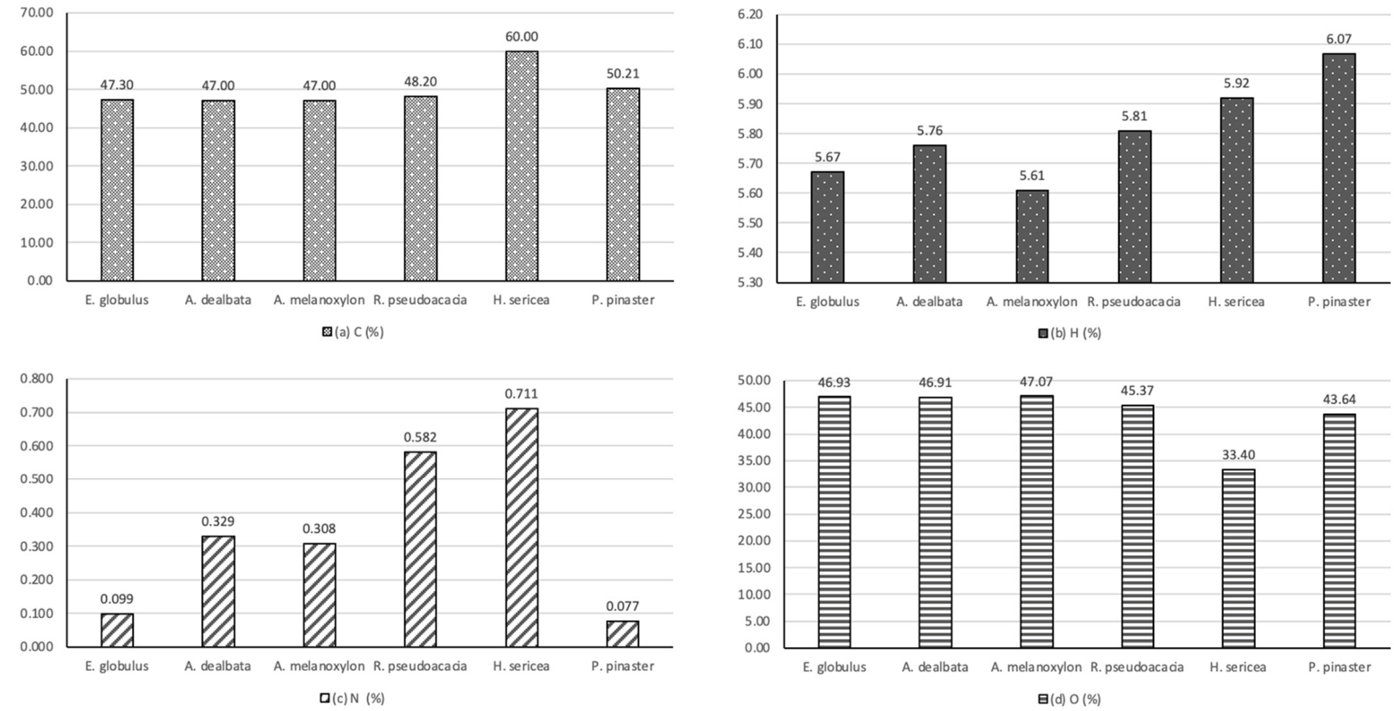

Figure 3. Results of the elemental analysis CHNO.

2.3. Determination of Sulfur and Chlorine Content

The results of the sulphur and chlorine content determination are shown in Figure 4.

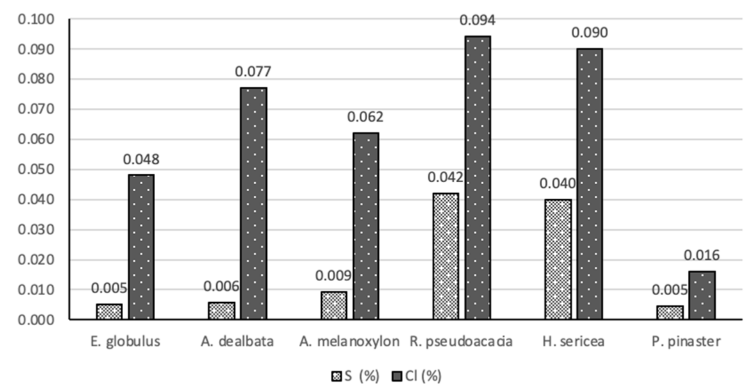

Figure 4. Sulphur and chlorine content.

The sulfur content varied between a minimum value of 0.005%, for *Eucalyptus globulus* and *Pinus pinaster*, and a maximum value of 0.042%, for *Robinia pseudoacacia*. The remaining species varied between 0.006% and 0.040%. The chlorine content varied between a minimum value of 0.016% for *Pinus pinaster* and a maximum value of 0.094% for *Robinia pseudoacacia*. The remaining species varied between 0.048% and 0.090%.

2.4. Determination of the High and Low Heating Value

The results of the heating value determination are shown in Figure 5.

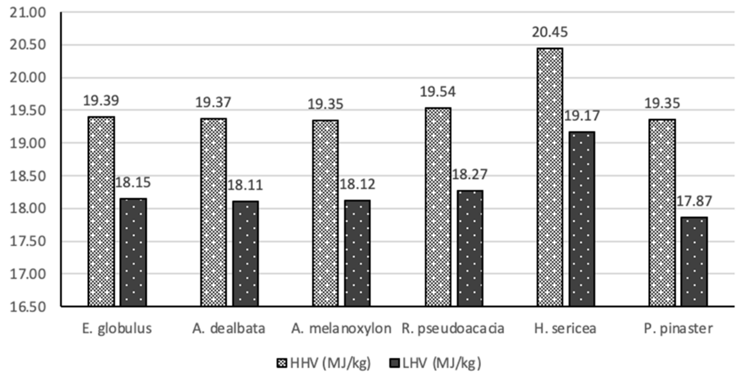

Figure 5. Higher heating value (HHV) and lower heating value (LHV) results.

The high heating value varied from the minimum value of 19.35 MJ/kg, for *Acacia melanoxylon* and for *Pinus pinaster*, to the maximum value of 20.45 MJ/kg, for *Hakea sericea*. The remaining species varied between 19.37 MJ/kg and 19.54 MJ/kg. The low heating value varied from the minimum value of 17.87 MJ/kg, for *Pinus pinaster*, to the maximum value of 19.17 MJ/kg, for *Hakea sericea*. The remaining species varied between 18.11 MJ/kg and 18.27 MJ/kg.

2.5. Determination of the Content of Major Elements

The results of the content of major elements are shown in Figure 6.

The Al content varied between a minimum value of 8.05 mg/kg for *Acacia dealbata* and a maximum value of 307.24 mg/kg for *Pinus pinaster*. The remaining species varied between 19.08 mg/kg and 215.18 mg/kg. The Ca content varied between a minimum value of 1645.15 mg/kg, for *Pinus pinaster*, and a maximum value of 21,917.90 mg/kg, for *Robinia pseudoacacia*. The remaining species ranged from 2214.41 mg/kg to 4830.83 mg/kg. The Fe content varied between a minimum of 21.51 mg/kg for *Acacia dealbata* and a maximum of 268.37 mg/kg for *Pinus pinaster*. The remaining species varied between 38.77 mg/kg and 187.90 mg/kg. The Mg content varied between a minimum of 564.19 mg/kg for *Acacia dealbata* and a maximum of 1474.89 mg/kg for *Robinia pseudoacacia*. The remaining species varied between 645.28 mg/kg and 1120.13 mg/kg. The P content varied from a minimum value of 78.08 mg/kg, for *Pinus pinaster*, up to a maximum value of 480.22 mg/kg. The remaining species varied between 124.93 mg/kg and 312.28 mg/kg. The K content varied from a minimum value of 723.84 mg/kg, for *Pinus pinaster*, up to a maximum value of 3848.58 mg/kg, for *Robinia pseudoacacia*. The remaining species ranged from 1427.42 mg/kg to 3003.84 mg/kg. The Si content varied from a minimum value of 5.13 mg/kg, for *Acacia melanoxylon*, to a maximum value of 993.31 mg/kg, for *Pinus pinaster*. The remaining species varied between 31.47 mg/kg and 856.28 mg/kg. The Na content varied between a minimum value of 436.79 mg/kg, for *Pinus pinaster*, and a maximum value of 1984.70 mg/kg, for *Hakea sericea*. The remaining species varied between 738.66 mg/kg and 1106.17 mg/kg. The Ti content varied between a minimum of 1.22 mg/kg for *Acacia dealbata* and a maximum of 19.22 mg/kg for *Pinus pinaster*. The remaining species ranged from 1.84 mg/kg to 15.68 mg/kg.

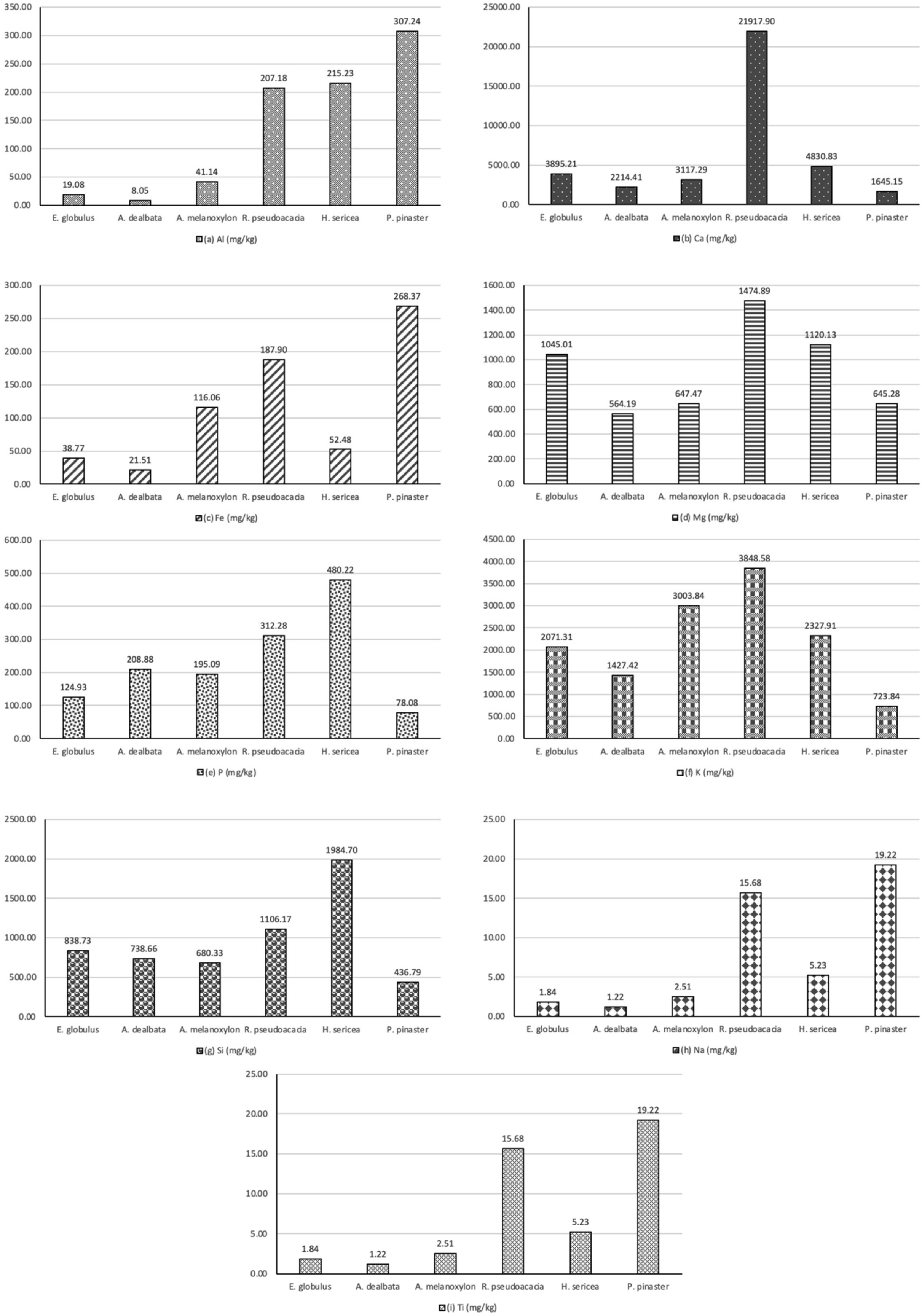

Figure 6. Content of major elements.

2.6. Determination of the Content of Minor Elements

The results of the content of minor elements are shown in Figure 7.

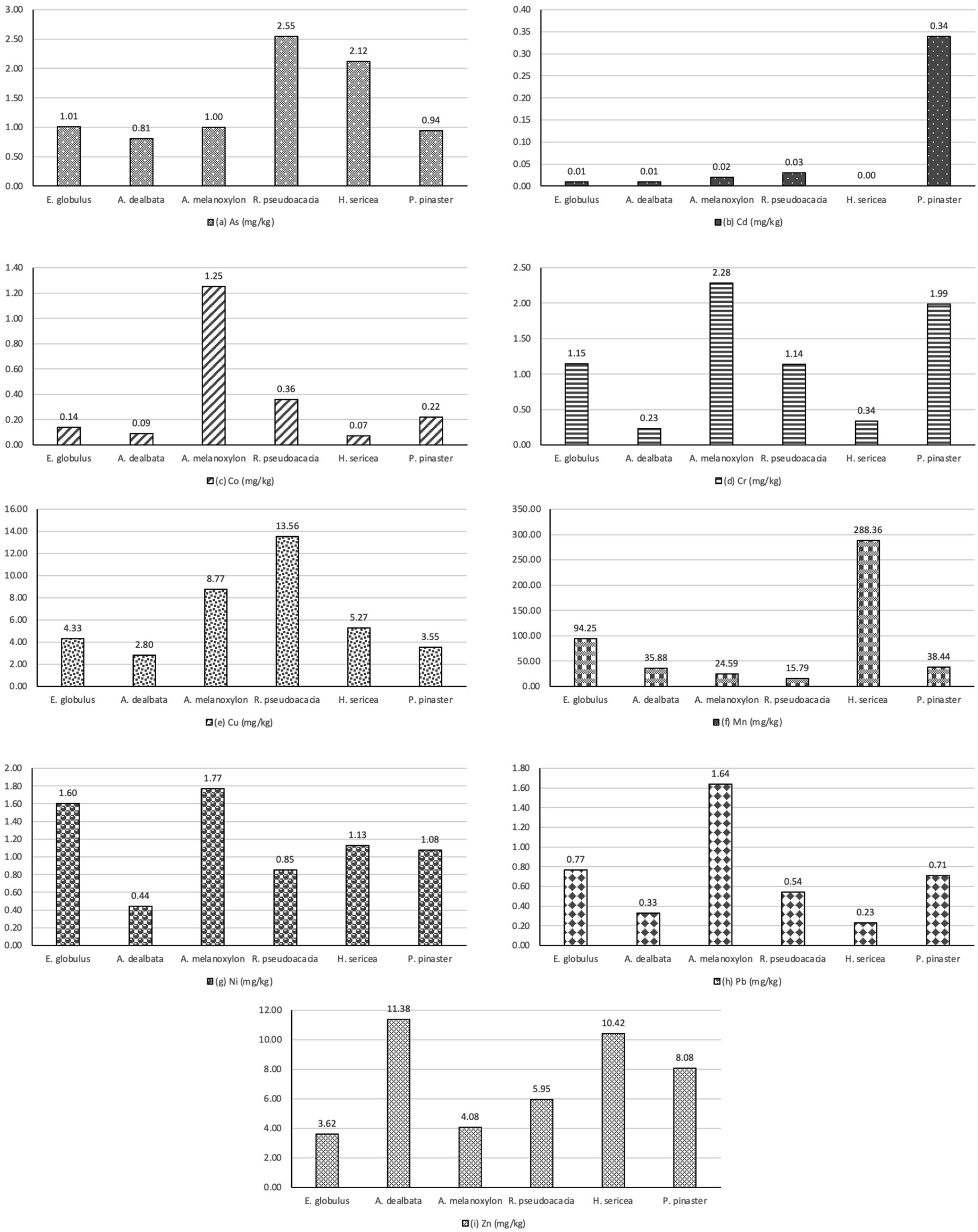

Figure 7. Content of minor elements.

The As content varied between the minimum value of 0.81 mg/kg, for *Acacia dealbata*, and the maximum value of 2.55 mg/kg, for *Robinia pseudoacacia*. The remaining species ranged from 0.94 mg/kg to 2.12 mg/kg. The Cd content varied between the minimum value of 0.00 mg/kg, for *Hakea sericea*, up to a maximum value of 0.34 mg/kg, for *Pinus pinaster.* The remaining species varied between 0.01 mg/kg and 0.03 mg/kg. The Co content varied between the minimum value of 0.07 mg/kg, for *Hakea sericea*, and the maximum value of 1.25 mg/kg, for *Acacia melanoxylon*. The remaining species varied between 0.09 mg/kg and 0.36 mg/kg. The Cr content varied between the minimum value of 0.23 mg/kg, for *Acacia dealbata*, and the maximum value of 2.28 mg/kg, for *Acacia melanoxylon*. The remaining species varied between 0.34 mg/kg and 1.99 mg/kg. The Cu content varied between the minimum value of 2.80 mg/kg, for *Acacia dealbata*, and the maximum value of 13.56 mg/kg, for *Robinia pseudoacacia*. The remaining species varied between 3.55 mg/kg and 8.77 mg/kg. The Mn content varied between the minimum value of 15.79 mg/kg, for *Robinia pseudoacacia*, and the maximum value of 288.36 mg/kg, for *Hakea sericea*. The remaining species varied between 24.59 mg/kg and 94.25 mg/kg. The Ni content varied between the minimum value of 0.44 mg/kg, for *Acacia dealbata*, and the maximum value of 1.77 mg/kg, for *Acacia melanoxylon*. The remaining species varied between 0.85 mg/kg and 1.60 mg/kg. The Pb content varied between the minimum value of 0.23 mg/kg, for *Hakea sericea*, and the maximum value of 1.64 mg/kg, for *Acacia melanoxylon*. The remaining species varied between 0.33 mg/kg and 0.77 mg/kg. The Zn content varied between the minimum value of 3.62 mg/kg, for *Eucalyptus globulus*, and the maximum value of 11.38 mg/kg. The remaining species varied between 4.08 mg/kg and 10.42 mg/kg.

2.7. Ash Fusibility

The results of the ash fusibility temperatures are shown in Figure 8.

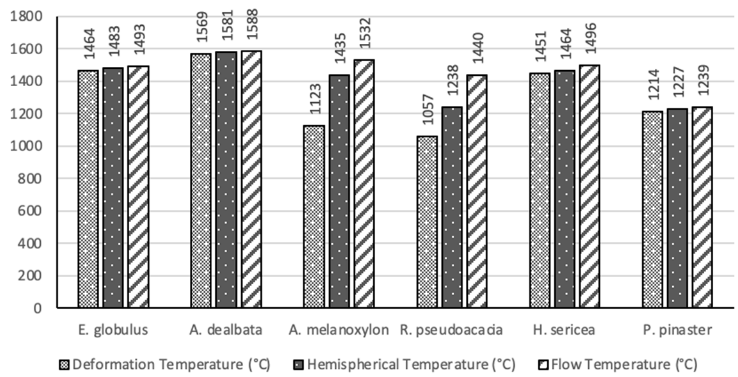

Figure 8. Ash fusibility temperatures.

Deformation temperatures ranged from the minimum value of 1057 °C, for *Robinia pseudoacacia*, and the maximum value of 1569 °C, for *Acacia dealbata*. The remaining species varied between 1123 °C and 1464 °C. Hemispherical temperatures varied between the minimum value of 1227 °C, for *Pinus pinaster*, and the maximum value of 1581 °C, for *Acacia dealbata*. The remaining species varied between 1238 °C and 1483 °C. The flow temperatures varied between the minimum value of 1239 °C, for *Pinus pinaster*, and the maximum value of 1588 °C, for *Acacia dealbata*.

3. Discussion

There are many works available where characterizations of the most diverse types of biomass are presented, in order to assess their combustibility and their physical-chemical properties. An example of this is the review work presented by Cai et al. (2017), where several lignocellulosic biomasses are characterized, including several residual biomasses of agricultural origin, such as rice husk, rice stalk, cotton stalk, wheat straw or corn stalk, but also residual biomasses of forest origin, like pine or poplar [22]. The objective of this study by Cai et al. (2017) fits that of many others, such as those presented by García et al. (2012), Chiang et al. (2012), Wilson et al. (2011), Fang et al. (2015) or Patel and Gami (2012), always from the perspective that using lignocellulosic biomass-derived biofuels can reduce reliance on fossil fuels and contribute to climate change mitigation [23–27]. Many works are also available regarding the behavior of different forms of biomass when subjected to thermochemical conversion processes, such as torrefaction, pyrolysis or gasification, such as the work of Chen et al. (2014), which addresses the non-oxidative and oxidative torrefaction characterization and SEM observations of fibrous and ligneous biomass [28], or the work of Neves et al. (2011), where biomass pyrolysis is addressed, regarding models, mechanisms, kinetics and some information on product yields and properties [29]. In fact, this perspective of energy recovery through the use of energy densification technologies foresees, at the outset, a need to improve, or in some way, correct, the less positive characteristics, such as low heating value, low density or high content of ashes. However, the most frequent uses presuppose the direct combustion of materials [30–32].

The comparative analysis of forms of residual biomass and their potential framing with premium raw materials, certified by the international standards in force, as is the case of ENplus ®, has also been addressed by extensive literature. For example, the work presented by Agar et al. (2018) addresses the production of pellets from agricultural and forest biomass [33], while de Souza et al. (2020) addressed the possibility of producing pellets from eucalyptus biomass and coffee growing wastes residues with acceptable properties for commercialization standards, which includes the ENplus ® standard [34]. In other words, the possibility of integrating different forms of biomass has been a necessity for a long time, since it would allow, in case of success and compliance with the quality criteria, the reduction in the cost of the acquisition of raw materials at the same time, which presents a solution for the disposal/reuse of a set of waste, which until now has not been subject to any type of recovery [13].

Thus, the classification of the properties of any residual raw material, as is the case of the species selected in the present study, with the parameters defined with one of the standards used internationally for the certification of fuels derived from biomass, as is the case of ENplus ® standard, allows, in a simple and accessible way, the validation or exclusion of the use of a certain material (species), or at least, it allows indicating whether it is possible to incorporate a certain percentage of these materials in any way [35]. Table 1 shows the values allowed for the main parameters indicated for the raw materials used in the production of wood pellets by the ENplus ® standard. This standard divides products into three categories according to the origin of the raw materials, with categories A2 and B destined to products resulting from the processing of waste materials, which include the species used in the present study [36]. However, in the case of incorporating percentages of residual biomass with premium raw materials, and if the parameters defined in the standard are met, the final products can be included in category A1, which has the highest added value [37].

The results obtained by the characterization of these biomass species, which are summarized in Table 2, present a relatively different framework. In the table, the values marked in italics represent the values that meet the requirements of categories A2 or B, and in bold, the values that do not fit into any of the categories. The remaining values are within the limits imposed by the ENplus ® A1 standard. As expected, *Pinus pinaster* fully complies with all the requirements presented by the ENplus ® standard, while none of the other species fully comply with all parameters. However, some of the species present values very close to the permitted limits, so that their incorporation with, for example, *Pinus pinaster*, appears as possible, and thus meet the requirements defined by the standard ENplus ®.

Table 1. Limit values for properties defined by the ENplus ® standard.

		ENplus ®		
		A1	**A2**	**B**
Moisture	%	≤10		
Ash	%	≤0.7	≤1.2	≤2
LHV	MJ/kg	≥16.50		
N	%	≤0.3	≤0.5	≤1.0
S	%	≤0.04		≤0.05
Cl	%	≤0.02		≤0.03
Deformation Temp.	°C	≥1200		≥1100
As	mg/kg	≤1		
Cd	mg/kg	≤0.5		
Cr	mg/kg	≤10		
Cu	mg/kg	≤10		
Pb	mg/kg	≤10		
Hg	mg/kg	≤0.1		
Ni	mg/kg	≤10		
Zn	mg/kg	≤100		

Table 2. Comparative analysis of the results obtained with the parameters defined by the ENplus ® standard.

		P.p.	***E.g.***	***A.d.***	***A.m.***	***R.p.***	***H.s.***
Moisture	%	6.42	8.98	7.54	9.28	7.61	6.85
Ash	%	0.62	*0.93*	0.52	*0.81*	**5.14**	*1.82*
LHV	MJ/kg	17.87	18.15	18.11	18.12	18.27	19.17
N	%	0.08	0.099	*0.329*	*0.308*	*0.582*	*0.711*
S	%	0.0045	0.005	0.006	0.009	*0.042*	0.040
Cl	%	0.016	**0.05**	**0.08**	**0.06**	**0.09**	**0.09**
Deformation Temp.	°C	1214	1464	1569	*1123*	**1057**	1451
As	mg/kg	0.94	**1.01**	0.81	1.00	**2.55**	**2.12**
Cd	mg/kg	0.34	0.00	0.00	0.00	0.03	0.00
Cr	mg/kg	1.99	1.15	0.23	2.28	1.14	0.34
Cu	mg/kg	3.55	4.33	2.80	8.77	**13.56**	5.27
Pb	mg/kg	0.71	0.77	0.33	1.64	0.00	0.23
Hg	mg/kg	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ni	mg/kg	1.08	1.60	0.44	1.77	0.85	1.13
Zn	mg/kg	8.08	3.62	11.38	4.08	5.95	10.42

As can be seen in the results presented in Table 2, the incorporation of these materials in the production of certifiable wood pellets, only seems possible for the biomass of *Eucalyptus globulus*, which would easily dilute the values above the requirements defined in the standard, allowing the incorporation of a percentage of 25%, which allows the production of wood pellets of category A1. An incorporation of 50% of *Eucalyptus globulus* biomass would only allow for category B certification, since the chlorine content would always be close to the upper limit of 0.03% indicated in the standard for this category. The remaining species present values that are too high in some parameters, namely in nitrogen content, with values ranging between 0.308% and 0.711%, mainly for *Hakea sericea* and *Robinia pseudoacacia*, but also due to the accumulation of other parameters outside the limits defined, as for the ash content, with *Robinia pseudoacacia* reaching 5.14%, and in the chlorine content, where it reaches 0.09%, together with Hakea sericea. However, the use of these residual biomasses remains possible, especially if the objective is not to produce certified materials, but rather to be used less domestically, and to support the local biomass recovery.

The local valorization of residual biomasses, as those analyzed in the present study, as well as others with similar properties, can always be a solution. Usually, given the lower requirement of the proximity markets, where the most evaluated requirement is the fuel cost, in detriment to the quality and combustibility requirements, such products can be used. The possibility of using these residual biomasses in thermochemical conversion processes, namely in the production of biochar, not as an energy product, but rather as a soil amendment product and as a carbon sequestration methodology, must be evaluated, with regard to the creation of value chains for residual biomass. This perspective of creating value chains, which aim to promote the maintenance of actions to control and eradicate invasive species, contributes systematically to the revitalization of ecosystems. This positive condition is effective when the pressure caused on the populations of invasive species decrease their strength, allowing native species to develop and return to occupy their space.

4. Materials and Methods

4.1. Sampling and Material Preparation

The species were selected for their availability and abundance and were collected in areas where their proliferation has been noted for the speed of propagation and occupation of space. Thus, the samples were collected in the locations shown in Table 3. Thus, samples of five invasive species were collected, namely, *Acacia dealbata*, *Acacia melanoxylon*, *Eucalyptus globulus*, *Robinia pseudoacacia* and *Hakea sericea*. Samples of *Pinus pinaster* were also collected to serve as a point of comparison. All samples were collected in the form of adult tree trunks, and in the case of invasive species, the all-in method was chosen. That is, none of the constituent parts, such as branches or leaves, have been discarded.

Table 3. Location of sample collection points used in the present study.

Species	Location
Acacia dealbata	Casal do Rei (Seia—Portugal)
Acacia melanoxylon	Loureiro (Oliveira de Azeméis—Portugal)
Eucalyptus globulus	Loureiro (Oliveira de Azeméis—Portugal)
Robinia pseudoacacia	Albernoa (Aljustrel—Portugal)
Hakea sericea	Casal do Rei (Seia—Portugal)
Pinus pinaster	Vale de Cambra (Portugal)

In the sample preparation procedure, the sequence used in a wood pellet production unit was followed, using exclusively *Pinus pinaster* as a raw material, so the *Pinus pinaster* wood was previously debarked before proceeding with the drying. The rest of the wood was not debarked, since the industrial debarking process used is optimized to operate only with *Pinus pinaster* logs, and if the other mentioned species were included in the process, this operation would not be carried out efficiently. Then, the size of the collected samples was reduced to a granulometry equivalent to that normally used in the industrial process, that is, to a G30 size woodchips, which was subjected to drying in a laboratory oven at 100 °C for a period of 12 h. After drying, the material of all samples was ground again, until the dimension normally used in the industrial process of wood pellet production was reached, with a d_{50} within the range [1.13–3.86]. Subsequently, the laboratory characterization of the samples followed with the thermogravimetric analysis, the elemental analysis, the calorimetric analysis, the chemical analysis and the analysis of the fusibility of the ashes. All samples were collected and analyzed in triplicate and the results presented are the average values for each species.

4.2. Thermogravimetric Analysis (TGA)

The thermogravimetric analyzer used was an ELTRA THERMOSTEP model. One gram of each sample was introduced into crucibles and placed inside an oven, along with an empty reference crucible. As temperature increased, crucibles were weighted on a precision scale. Moisture, volatiles, and fixed carbon content were determined in this order throughout the heating process. Lastly, the final residue represents the ash content.

4.3. Elemental Analysis (CHNO)

Elemental analysis was performed in a LECO CHN628. The operational principle consists of weighing a sample in tin foil that is later placed in the autoloader. The sample is then introduced into the primary furnace containing only pure oxygen, which results in fast and complete combustion. Carbon, hydrogen, and nitrogen present in the sample are oxidized to CO_2, H_2O, and NO_x, respectively, and are swept by the oxygen carrier gas through a secondary furnace for further oxidation and particulate removal. Detection of H_2O and CO_2 occurs through separate, optimized, non-dispersive infrared cells, while the NO_x gases are reduced to N. Lastly, N_2 is detected when the gas passes through a thermal conductivity cell. After the analysis is complete, moisture content obtained through thermogravimetric analysis is introduced into the software and the CHN contents are automatically calculated. Following that, it is possible to estimate the oxygen content on a dry basis ($w_{O,db}$) from Equation (1), as follows:

$$w_{O,db}\ (\%) = 100 - w_{C,db} - w_{H,db} - w_{N,db} - w_{S,db} - w_{Cl,db}, \quad (1)$$

where $w_{C,db}$ is the carbon content on a dry basis (%), $w_{H,db}$ is the hydrogen content on a dry basis (%), $w_{N,db}$ is the nitrogen content on a dry basis (%), $w_{S,db}$ is the sulfur content on a dry basis (%), and $w_{Cl,db}$ is the chlorine content on a dry basis (%).

4.4. Determination of Chlorine Content

Chloride titration was the method chosen to determine the chlorine content, and the equipment used was a TITROLINE 7000 titrator from SI Analytics. For this procedure, sample preparation involves previous digestion of the sample, performed in a SINEO MDS-6G microwave, since titration requires a liquid sample. Chlorine content determination is achieved by potentiometric titration. This method consists of measuring the potential difference while the titrant, in this case, $AgNO_3$, is added. Equation (2), as follows, presents the redox reaction that occurs:

$$Cl^{-}{}_{(aq.)} + AgNO_{3(aq.)} \rightarrow AgCl_{(S)} + NO_{3\ (aq.)}^{-}, \quad (2)$$

As next step, a software creates a spreadsheet with the potential difference and titrant volume variation over time. First derivative can then be calculated through Equation (3), as follows, and the equivalence point can be determined as the volume corresponding to the maximum of the first derivative:

$$f'(x) = \frac{\Delta U}{\Delta V} = \frac{U_i - U_{i-1}}{V_i - V_{i-1}} f'(x) = \frac{\Delta U}{\Delta V} = \frac{U_i - U_{i-1}}{V_i - V_{i-1}}, \quad (3)$$

where ΔU is the potential difference variation (mV) and ΔV is the volume variation (mL).

Chlorine content on a dry basis ($w_{Cl,db}$) is then determined by Equation (4), in compliance with the European standard EN15289:

$$w_{Cl,db}\ (\%) = \frac{(C - C_0) \times V}{m} \times 100 \times \frac{100}{100 - M_{ad}} w_{Cl,db}(\%) = \frac{(C - C_0) \times V}{m} \times d \times \frac{100}{100 - M_{ad}}, \quad (4)$$

where C is the concentration of chloride in the solution (mg/L), C_0 is the concentration of chloride in the blank solution (mg/L), V is the volume of the solution (l), m is the mass of the test portion used in the digestion (mg), and M_{ad} is the moisture content in the analysis test sample (%).

4.5. Heating Value

Heating value, also known as the heating value, defines the energy content of biomass fuel [38]. This parameter can be described in two ways: higher heating value (HHV), or gross heating value, refers to the heat released from fuel combustion along with the vaporization energy from water. On the other hand, lower heating value (LHV) or net heating value is based on steam as the product, which means its vaporization energy is not considered heat [39]. The heating value of biomass, both higher and lower, can be determined experimentally by employing an adiabatic bomb calorimeter. The model used in this project was the 6400 Automatic Isoperibol Calorimeter by PARR INSTRUMENT. After each procedure, the equipment provides the corrected temperature increase that is later used for the determination of the heating value. Due to the nitrogen and oxygen-rich atmosphere inside the calorimeter, nitric acid and sulphuric acid are formed, respectively, and the heat of formation of both acids must be disregarded. For HNO_3, the wash water for the pump was titrated with NaOH (0.1 M), and Equation (5) was applied, while for H_2SO_4, knowing the sulfur content Equation (6) can be applied:

$$Q_{N,S} = 1.43 \times V_{NaOH}, \tag{5}$$

where $Q_{N,S}$ is the heat contribution relative to nitric acid formation (cal) and V_{NaOH} is the volume of NaOH used in the titration of the wash water of the pump (ml).

$$Q_{S,add} = 13.61 \times w_{S,db}, \tag{6}$$

where $Q_{S,add}$ is the additional contribution relative to sulfur dioxide formation and $w_{S,db}$ is the sulfur content on a dry basis (%).

With this information, Equation (7) can be applied to obtain the gross heating value, or high heating value, at a constant volume, $q_{V,gr}$ (J/g), as follows:

$$q_{V,gr} = \left(\frac{\varepsilon \times \theta - Q_{thread} - Q_{N,S}}{m} - Q_{S,add} \right) \times 4.1868, \tag{7}$$

where ε is the heating capacity of the calorimeter (previously determined) (cal/°C), θ is the corrected temperature increase (°C), Q_{thread} is the heat contribution relative to the thread combustion (cal), $Q_{N,S}$ is the heat contribution relative to nitric acid formation (cal), $Q_{S,add}$ is the additional contribution relative to sulfur dioxide formation (cal), and m is the mass of the sample (g).

Equation (8) was used to calculate the gross heating value at constant volume on a dry basis, $q_{V,gr,db}$ (J/g), as follows:

$$q_{V,gr,db} = q_{V,gr} \times \frac{100}{100 - M_{ad}} q_{V,gr,db} = q_{V,gr} \times \frac{100}{100 - M_{ad}}, \tag{8}$$

where $q_{V,gr,db}$ is the gross heating value at constant volume (J/g) and M_{ad} is the moisture content in the analysis test sample (%). Lastly, the net heating value at constant pressure on a dry basis, $q_{p,net,db}$ (J/g), can be calculated through Equation (9), as follows:

$$q_{p,net,db} = q_{V,gr,db} - 212.2 \times w_{H,db} - 0.8 \times (w_{O,db} + w_{N,db}), \tag{9}$$

where $q_{V,gr,db}$ is the gross heating value at constant volume on a dry basis (J/g), $w_{H,db}$ is the hydrogen content on a dry basis (%), $w_{O,db}$ is the oxygen content on a dry basis (%), and $w_{N,db}$ is the nitrogen content on a dry basis (%). According to the European standard EN14918, ($w_{O,db}$ + $w_{N,db}$) is obtained from Equation (10), as follows:

$$(w_{O,db} + W_{N,db}) = 100 - w_{A,db} - w_{C,db} - w_{H,db} - w_{S,db} \tag{10}$$

where $w_{A,db}$ is the ash content on a dry basis (%), $w_{C,db}$ is the carbon content on a dry basis (%), $w_{H,db}$ is the hydrogen content on a dry basis (%), and $w_{S,db}$ is the sulfur content on a dry basis (%).

4.6. Chemical Analysis by ICP-OES

Inductively coupled plasma atomic emission spectroscopy (ICP-AES), also known as inductively coupled plasma optical emission spectrometry (ICP-OES), is an analytical technique, which produces excited atoms and ions that emit electromagnetic radiation at different wavelengths and is used for the determination of trace elements. The main advantages are its multi-element capability, broad dynamic range, and effective background correction [40]. For the preparation of the samples, microwave digestion was once again necessary to ensure that the capillaries did not get obstructed. The model used for the analysis was a THERMO SCIENTIFIC (iCAP 6000 series). A peristaltic pump delivered the digested samples to an analytical nebulizer and introduced them into the plasma flame that breaks down the samples into charged ions, releasing radiation with specific wavelengths. In the end, a software generates a spreadsheet with the results. Equations (11) and (12) were used, as follows, to calculate the content of each element in the sample on a dry basis ($w_{i,db}$), in compliance with standards EN15289, EN15290 and EN15297:

$$w_{i,db} = \left(\frac{mg}{kg}\right) = \frac{(C - C_{i,0}) \times V}{m} \times \frac{100}{100 - M_{ad}} \quad (11)$$

where C_i is the concentration of the element in the diluted sample digest (mg/L), $C_{i,0}$ is the concentration of the element in the solution of the blank experiment (mg/L), V is the volume of the diluted sample digest solution (mL), m is the mass of the test portion used (g), and M_{ad} is the moisture content in the analysis test sample (%).

$$w_{S,db}\ (\%) = \frac{(C - C_0) \times V}{m} \times 0.3338 \times 100 \times \frac{100}{100 - M_{ad}} \quad (12)$$

where C_i is the concentration of sulfate in the solution (mg/L), $C_{i,0}$ is the concentration of sulfate in the solution of the blank experiment (mg/L), V is the volume of the diluted sample digest solution (mL), m is the mass of the test portion used (g), 0.3338 is the stoichiometric ratio of the relative molar masses of sulfur and sulfate, and M_{ad} is the moisture content in the analysis test sample (%).

4.7. Fusibility of the Ashes

This determination makes it possible to estimate the behavior of biomass ash when combustion is carried out, for example, in boilers or burners. During the combustion process, ashes may occur, such as slagging and fouling. Slagging is the deposit of ash in the bottom and walls of the furnaces, while fouling is the deposit of ash in the air flow zones (which can cause clogging of pipes). The formation of slagging and fouling depends on the ash content of a biomass, as well as on the elemental composition of the ash. The determination of ash fusibility consists of monitoring the behavior of ash melting along a temperature ramp. Thus, this test allows to predict the formation of slagging and fouling in thermal conversion processes. These data must be related to the ash content (determined using the TGA) and the content of the different ash components (determined by ICP/OES). The fusibility test can be carried out with an oxidizing atmosphere (air) or reducing atmosphere (60% CO + 40% CO_2). The choice of atmosphere must be related to the combustion conditions of the boiler or burner. If the boiler operates in atmospheres rich in fuel (with oxygen deficit), its atmosphere will be mostly reducing, with incomplete combustion and CO formation. As a general rule, reducing atmospheres cause ash to melt at lower temperatures, thus causing greater slagging and fouling problems. Therefore, the fuse test must reflect these characteristics and adapt to the customer's combustion process. During the fusibility test, the ash melting behavior is monitored and the following characteristic temperatures are determined:

- Initial temperature: temperature at which the test starts up to 550 °C;
- Shrinking temperature: shrinkage to 95% of the area recorded at 550 °C;
- Deformation temperature: temperature at which the first rounding of the vertices of the cylinders occurs;
- Hemisphere temperature: temperature at which the height of the cylinder is equal to half the width;

- Fluid temperature: temperature at which the height is equal to half the height recorded at the hemisphere temperature.

In the present study, the samples, converted to ashes, were subsequently placed in a plastic dish, where two drops of ethyl alcohol are added, and using a spatula they are homogenized until a uniform paste is obtained. Then this paste is transferred to the mold, where the cylinder is compacted. After being removed from the mold, the cylinders are placed on the zirconia lamella. The samples are then placed inside the chamber of the ash fusibility furnace, which in this specific case was a SYLAB IF 2000-G device.

5. Conclusions

The use of residual biomass in the production of wood pellets is an opportunity for the circularization of the local economy associated with forest management operations. It also presents itself as an opportunity for the sustainability of operations to control invasive species, as it contributes to the creation of value chains for residual products that until now had no added value. The incorporation of these materials in the production of certified wood pellets presents some difficulties, since these materials do not meet the chemical requirements imposed by the standards that regulate the quality of the final products. However, the recovery of residual biomass from actions to control and eradicate invasive species can be a reality, especially for uses that do not imply product certification, and especially when the recovery of materials in industrial environments is not involved, where adverse effects, such as corrosion, fouling or slagging, can result in serious damage and unforeseen maintenance to combustion equipment.

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CHAPTER 4 – Control of Invasive Species

Chapter Index

fire

Article

Acacia dealbata Link. Aboveground Biomass Assessment: Sustainability of Control and Eradication Actions to Reduce Rural Fires Risk

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Abstract: Invasive species are an environmental problem affecting worldwide ecosystems. In the case of *Acacia dealbata* Link., the negative impacts affect the productivity of the forests due to the competition established with native species while contributing to a significant increment in the available fuel load, increasing the risk of fire. In Portugal, chemical and mechanical methods are mostly used in the control of these species. However, the costs are often unsustainable in the medium term, being abandoned before completing the tasks, allowing the recovery of the invasive species. The establishment of value chains for the biomass resulting from these actions was pointed out by several authors as a solution for the sustainability of the control process, as it contributes to reducing costs. However, the problems in quantifying the biomass availability make it challenging to organize and optimize these actions. This work, which started from a dendrometrical analysis carried out in stands of *A. dealbata*, created a model to assess woody biomass availability. The model proved to be statistically significant for stands with trees younger than 20 years old. However, the amount of data collected and the configuration of the settlements analyzed do not allow extrapolation of the model presented to older settlements.

Keywords: *Acacia dealbata* Link; invasive species; control and eradication actions; value chains; sustainability; rural fires

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1. Introduction

Acacia dealbata Link. is a species of Australian origin that has shown very aggressive invasive behavior in certain locations in Europe, namely in certain specific habitats and protected areas, such as coastal dunes, riparian zones, natural parks, and other protected areas, but also in agricultural areas or in the borders of forest areas [1–3]. Lorenzo et al. (2010) pointed out human interference, more specifically, soil disturbance and severe fires, as the main causes of the spread of *A. dealbata* in different habitats [4]. The same authors, corroborated by others, also presented the main impacts on ecosystems directly associated with the invasion and prevalence of *A. dealbata* in invaded ecosystems, namely the negative effects on native biodiversity [5–7]. Figure 1 shows the actual distribution of *A. dealbata* in Europe.

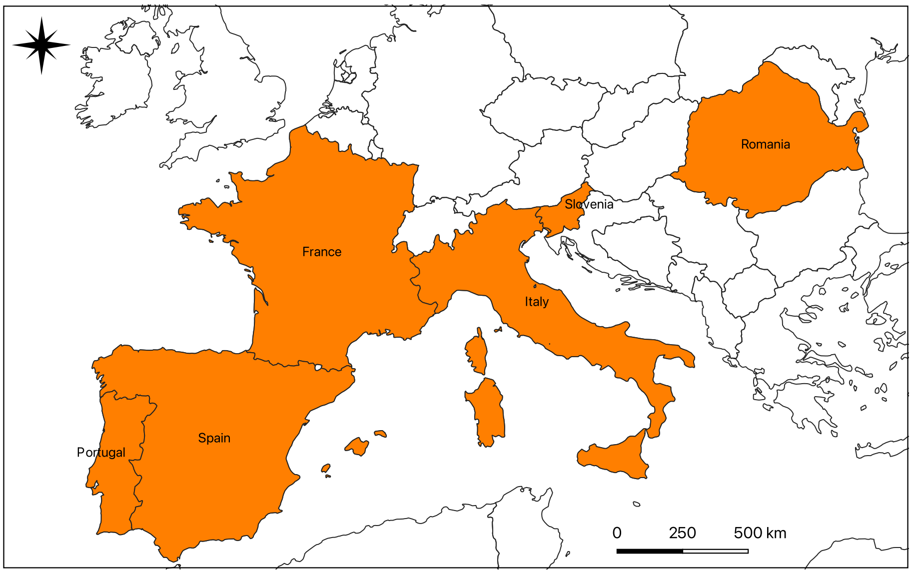

Figure 1. Distribution of *A. dealbata* in Europe (data collected from [8]).

This ability of *A. dealbata* to disperse seems to be related to a set of properties that the species presents, which even allow it to severely interfere with the balance of microorganisms in the soil. This ability, as noted by Lorenzo et al. (2010) allows *A. dealbata* to thrive through changes in microscopic communities. For example, it promotes increased bacterial activity in the soil, which is perhaps more advantageous for the species, while, on the other hand, the authors observed a decrease in fungal activity [9]. The authors also refer to changes in the chemical composition of the soil, which was later confirmed by other works, such as that of González-Munõz et al. (2012), with the authors demonstrating that *A. dealbata* alters the chemical composition of soils, with an increase in the content of nitrogen compounds and a lowering of the pH, contributing to the seeds of other species finding it more difficult to germinate [2]. Allelopathy has also been presented as a competitive advantage that this species presents, not only due to the presence of compounds in the soil that interfere with the development of other species but also due to the passage of rainwater through the foliage of the canopy of the trees. *A. dealbata*, mainly during the flowering period, as presented by Lorenzo et al. (2008), proves the ability of this species to aggressively dominate the space and with a competitive capacity that goes far beyond the ability that native species have [10]. This ability of the leachates of *A. dealbata* had already been reported by Carballeira et al. (1999), who tested the allelopathic capacity of these leachates in the growth of lettuce and concluded that the samples showed very significant toxicity [11].

This set of arguments led to the growing need to find ways to control and eradicate the species, to avoid its growing dispersion in different habitats, putting native biodiversity at risk [12,13]. However, the forms of control employed so far have not shown to be efficient and have not been able to prevent the advance of the species [14]. These control processes focused mainly on chemical and mechanical processes, as indicated by Campbell et al. (1990), who also described the use of controlled fire. This seems, however, not to contribute to the elimination of plants but rather to their recurrence with greater intensity in burnt areas, especially when there were previously adult stands with the capacity to create seed banks in the soil that germinate with great intensity after the use of fire, since *A. dealbata* is a pyrophyte species [15–17].

The possibility of creating value chains with the biomass of *A. dealbata*, as presented by Nunes et al. (2020), seems to be a methodology capable of contributing to the maintenance of control actions for longer periods of time so that pressure is exerted on the species, not giving it the ability to recover and, thus, continue its expansive process [18]. Control actions are often abandoned because of their costs, which often make it impossible to continue the work. The creation of value chains for biomass resulting from the control actions of *A. dealbata* can allow the sustainability of these actions, allowing their continuity. With this objective in mind, it seems to be essential to develop a tool that allows the expeditious quantification of the quantities of biomass available, so that the campaigns for the collection of biomasses can be optimized. They can be used later, for example, to produce firewood for domestic consumption, for incorporation in the production of biomass pellets, or in the production of charcoal [19,20]. Thus, the main objective of the present work is the development of a mathematical model aimed at quantifying the biomass of *A. dealbata* available in each area, for example, using aerial photography, where the various existing stands are delimited, allowing the organization of actions to control and forward the biomass resulting from these actions.

2. Materials and Methods

2.1. Framework and Selection of the Sampling Zone

There are several works that point to examples of protected areas that suffer the invasion of *A. dealbata*. In Portugal, this is a recurrent situation, with this species reaching both the coastal regions and the inland regions of the country, more specifically, for example, in the Peneda-Gerês National Park, or in the Serra da Estrela Natural Park, as shown in the works by Liberal et al. (1999), or Raposo et al. (2021) [14,21]. Thus, to carry out this work, an area located in the Serra da Estrela Natural Park was selected, specifically in the União de Freguesias de Cabeça e Vide, in the municipality of Seia, in the district of Guarda (Figure 2).

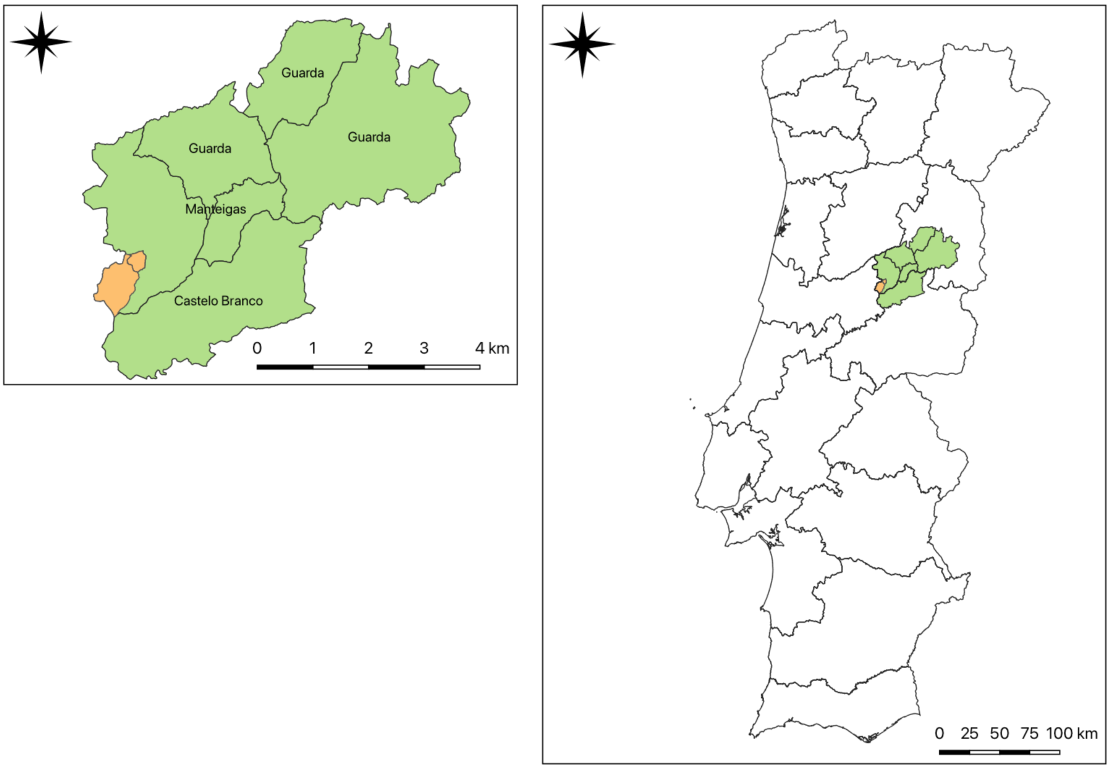

Figure 2. Location of the study area, in the União de Freguesias de Cabeça e Vide, in the municipality of Seia, in the district of Guarda.

Settlements of *A. dealbata* existing in the territory of the area selected for the study were first identified using a satellite image from August 2018, acquired using the Sentinel-2 plugin for QGIS software, version 3.18.1—Zurich. The settlements were later confirmed with on-site visits and delimited using QGIS to assess the area of each one of the settlements. For the data acquisition, one of the settlements was selected, where two circular transepts were established. These two transepts, designated by Parcel 1 and by Parcel 2, were established and selected to collect samples of *A. dealbata* specimens that were representative of existing settlements in the region, including specimens in different stages of development and from different ages. The transepts were established starting from a central point, which served to delimit a circle with a radius of 15 m, corresponding to an area of approximately 710 m^2, within which all existing trees were catalogued, with the collection of the following information: species, distance to the center of the transept (m), direction (°), and diameter at chest height (cm). Table 1 shows the data collected for each of the plots.

Table 1. Data collected in Parcels 1 and 2 (Ad—*Acacia dealbata*; Au—*Arbutus unedo*; Pp—*Pinus pinaster*; n/a—not applicable).

Parcel	Species	Tree nr.	Distance (m)	Direction (°)	Direction (rad)	d_1 (cm)	d_2 (cm)	d_{med} (cm)	Class d_{med}
1	Ad	1	0.73	4	0.0698	4.7	4.8	4.75	5
1	Ad	2	1.8	30	0.5236	5	4.6	4.8	5
1	Ad	3	3.3	5	0.0873	10.6	9.9	10.25	15
1	Ad	4	4.1	5	0.0873	4.4	3.7	4.05	5
1	Ad	5	3.9	10	0.1745	7.1	6.7	6.9	10
1	Ad	6	4.8	60	1.0472	9.7	7.2	8.45	10
1	Au	7	4.5	85	1.4835	n/a	n/a	n/a	n/a
1	Ad	8	3.6	90	1.5708	30.4	31	30.7	35
1	Ad	9	4.5	100	1.7453	6.8	6.8	6.8	10
1	Ad	10	5.1	85	1.4835	4.3	4.2	4.25	5
1	Ad	11	5.1	90	1.5708	5	5.6	5.3	10
1	Ad	12	5.2	97	1.693	4.2	4.1	4.15	5
1	Ad	13	5.2	98	1.7104	6.5	6.8	6.65	10
1	Ad	14	5.2	99	1.7279	3.5	3.5	3.5	5
1	Ad	15	5.6	97	1.693	3.7	3.7	3.7	5
1	Ad	16	5.2	100	1.7453	8.1	8	8.05	10
1	Ad	17	4.4	101	1.7628	5.4	5.6	5.5	10
1	Au	18	4.2	100	1.7453	4.3	4	4.15	5
1	Ad	19	5.1	115	2.0071	14.6	15.2	14.9	15
1	Ad	20	5.3	126	2.1991	12.5	12.2	12.35	15
1	Ad	21	4.2	117	2.042	5.9	5.7	5.8	10
1	Ad	22	5.45	130	2.2689	4.6	4.5	4.55	5
1	Ad	23	5.4	129	2.2515	3.4	3.6	3.5	5
1	Pp	24	5.35	130	2.2689	n/a	n/a	n/a	n/a
1	Ad	25	5.6	138	2.4086	8.2	9	8.6	10
1	Ad	26	5.3	141	2.4609	17.4	16.7	17.05	20
1	Ad	27	5.4	143	2.4958	4.3	4.1	4.2	5
1	Ad	28	5.6	155	2.7053	6.7	6.4	6.55	10
1	Ad	29	5.3	160	2.7925	4.4	4.5	4.45	5
1	Ad	30	5.3	162	2.8274	8.3	8.4	8.35	10
1	Ad	31	2.9	186	3.2463	17.9	18.2	18.05	20
1	Ad	32	3.5	185	3.2289	8.5	8.4	8.45	10
1	Ad	33	1.9	196	3.4208	16.7	16.7	16.7	20
1	Ad	34	2.3	210	3.6652	5.2	5.3	5.25	10
1	Ad	35	1.8	220	3.8397	5.2	4.7	4.95	5
1	Ad	36	1.8	235	4.1015	10.1	10	10.05	15
1	Ad	37	5.4	222	3.8746	16.6	15.2	15.9	20
1	Ad	38	5.0	230	4.0143	3.4	3.3	3.35	5
1	Ad	39	5.6	242	4.2237	13	13	13	15
1	Ad	40	5.3	244	4.2586	22.2	21.6	21.9	25
1	Ad	41	4.1	245	4.2761	11.7	10.8	11.25	15
1	Ad	42	4.0	258	4.5029	4.3	4.4	4.35	5
1	Ad	43	4.8	272	4.7473	4.6	5.2	4.9	5

Table 1. *Cont.*

Parcel	Species	Tree nr.	Distance (m)	Direction (°)	Direction (rad)	d_1 (cm)	d_2 (cm)	d_{med} (cm)	Class d_{med}
1	Ad	44	4.4	290	5.0615	4.5	4	4.25	5
1	Ad	45	4.2	295	5.1487	10.8	10.2	10.5	15
1	Ad	46	3.9	310	5.4105	16.7	17.8	17.25	20
1	Ad	47	3.9	320	5.5851	14.5	16.4	15.45	20
1	Ad	48	4.1	340	5.9341	14.2	15.6	14.9	15
1	Ad	49	5.2	0	0	4.6	4.8	4.7	5
1	Ad	50	5.4	2	0.0349	14.3	15.4	14.85	15
1	Ad	51	5.5	5	0.0873	3.6	3.2	3.4	5
1	Ad	52	5.6	20	0.3491	7.4	8.7	8.05	10
2	Ad	1	3.5	62	1.0821	6.1	6	6.05	10
2	Ad	2	5.3	114	1.9897	10.4	11.5	10.95	15
2	Ad	3	5.3	115	2.0071	10.7	11.3	11	15
2	Ad	4	5.5	116	2.0246	4.4	4.7	4.55	5
2	Ad	5	5.5	120	2.0944	10.4	11.3	10.85	15
2	Ad	6	5.4	123	2.1468	5.8	5.6	5.7	10
2	Ad	7	5.6	138	2.4086	11.9	13.7	12.8	15
2	Ad	8	4.5	150	2.618	6.3	5.9	6.1	10
2	Ad	9	5.0	158	2.7576	14	15.2	14.6	15
2	Ad	10	4.7	165	2.8798	9.7	9.6	9.65	10
2	Ad	11	5.0	165	2.8798	4.6	4.5	4.55	5
2	Ad	12	5.0	168	2.9322	9.1	10	9.55	10
2	Ad	13	5.6	168	2.9322	13.2	12.4	12.8	15
2	Ad	14	1.8	185	3.2289	3.4	3.2	3.3	5
2	Ad	15	1.0	195	3.4034	23.2	20.4	21.8	25
2	Ad	16	1.5	200	3.4907	4.6	4.5	4.55	5
2	Ad	17	3.8	225	3.927	6.4	6.3	6.35	10
2	Ad	18	4.9	227	3.9619	9.3	9	9.15	10
2	Ad	19	3.5	239	4.1713	4	4	4	5
2	Ad	20	1.7	265	4.6251	5.5	6.8	6.15	10
2	Ad	21	4.0	318	5.5501	16.9	19.6	18.25	20
2	Ad	22	4.8	305	5.3233	12.6	14.3	13.45	15
2	Ad	23	5.6	286	4.9916	9	8.5	8.75	10
2	Pp	24	5.0	285	4.9742	n/a	n/a	n/a	n/a
2	Ad	25	5.0	303	5.2883	4.1	4	4.05	5
2	Ad	26	3.7	315	5.4978	8.8	9.4	9.1	10
2	Ad	27	3.4	328	5.7247	6.4	6	6.2	10
2	Ad	28	2.0	323	5.6374	5.7	6.2	5.95	10
2	Ad	29	1.9	323	5.6374	5.3	5	5.15	10
2	Ad	30	4.5	326	5.6898	13.3	12.7	13	15
2	Ad	31	1.8	98	1.7104	7.7	8.8	8.25	10

Subsequently, 20 trees were selected as being representative of all existing diameter classes, defined as shown in Table 2.

Table 2. Diameter classes existing in Parcels 1 and 2.

Diameter Classes	DCH Range (cm)
Class 5	<5
Class 10	5–10
Class 15	10–15
Class 20	15–20
Class 25	20–25
Class 30	25–30
Class 35	30–35
Class 40	35–40

2.2. Samples Preparation

The selected trees were cut, and the following parameters were subsequently measured: trunk height (m), canopy height (m), total height (m), canopy diameter (m), trunk weight (kg), and weight of the branches (kg), which together provide the total weight of the aboveground biomass of each tree (kg). In Figure 3, the different stages of the cutting process and obtaining the measurement data are presented.

(**a**) (**b**)

Figure 3. Steps in the process of sampling with (**a**) cutting and measuring the *A. dealbata* trees and (**b**) weighing the selected specimens.

A section of the trunk near the base was also cut to determine the age of each one of the specimens. These discs were later polished and digitized to allow identification of the growth rings, as shown in Figure 4.

(**a**) (**b**) (**c**)

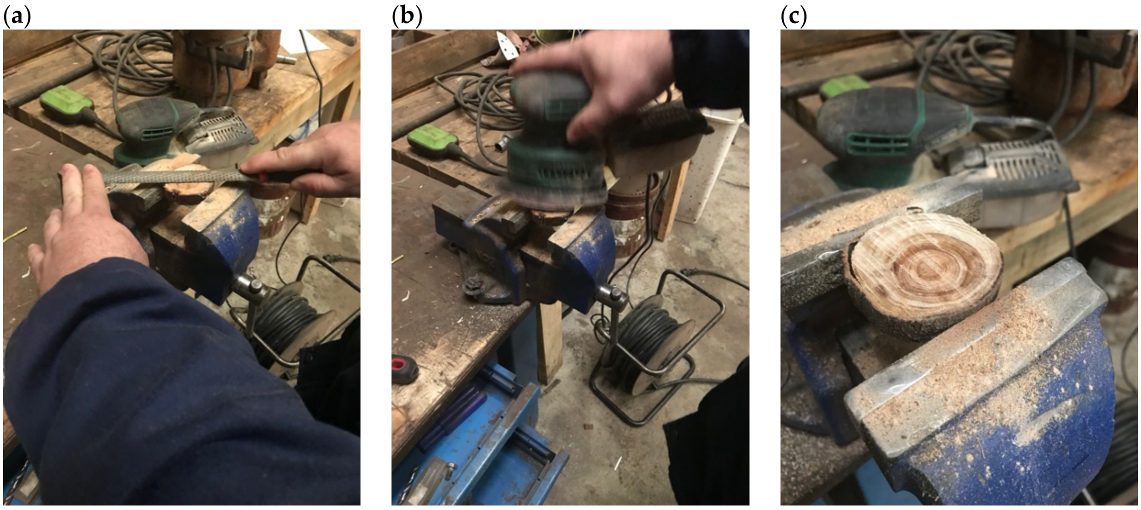

Figure 4. *Cont.*

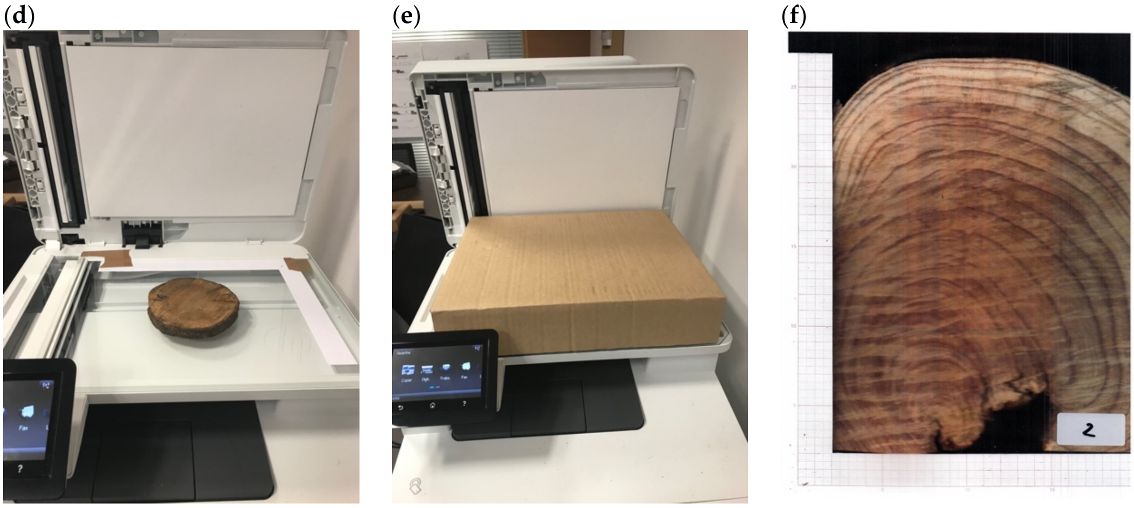

Figure 4. Sequence of the growth ring identification process to determine the age of selected specimens. (**a**) Coarse polishing of the samples, (**b**) fine polishing of the samples, (**c**) final aspect after polishing, (**d**) placing the samples to be digitalized, (**e**) covering the sample to create a dark chamber, and (**f**) digital image of the sample.

2.3. Data Processing and Creation of the Mathematical Model

For the treatment of the obtained data and development of the mathematical model, Microsoft® Excel, version 16.54, and IBM® SPSS Statistics, version 27.0.1.0 (64-bit edition), were used.

2.4. Validation of the Developed Model

After the creation of the mathematical model, it was applied to assess the amount of biomass of *A. dealbata* available in the settlements identified in the União de Freguesias de Cabeça e Vide.

3. Results

3.1. Characterization of the Selected Samples

The results obtained and calculated for the selected samples are shown in Table 3.

From the data obtained by direct measurement, such as height, weight, trunk diameter at chest height, or crown diameter, the area occupied by the crown was also determined, as this is understood to be the factor to be used in the creation of the mathematical model for estimating the biomass of stands. The trunk height parameter (h_t) presented a minimum value of 5.8 m and a maximum value of 17.75 m, with an average value of 13.78 $\pm$ 4.5 m. The canopy height (h_c) had a minimum value of 3 m and a maximum value of 11 m, with an average value of 4.0 $\pm$ 2.4 m. The total height (h_{total}) presented a minimum value of 8.8 m and a maximum value of 32.7 m, with an average value of 18.19 $\pm$ 6.3 m. The crown diameter presented a minimum value of 1 m and a maximum value of 9.5 m, with an average value of 2.3 $\pm$ 2.0 m. The diameter at chest height (DCH) had a minimum value of 4.2 cm and a maximum value of 30.7 cm, with a mean value of 9.95 $\pm$ 7.2 cm. The trunk weight presented a minimum value of 3.6 kg and a maximum value of 578.9 kg, with an average value of 48.75 $\pm$ 142.5 kg. The weight of the branches presented a minimum value of 1.8 kg and a maximum value of 25.5 kg, with an average value of 4.75 $\pm$ 9.2 kg. The total weight presented a minimum value of 5.5 kg and a maximum value of 594.8 kg, with an average value of 51.2 $\pm$ 149.1 kg. Age presented a minimum value of 5 years and a maximum value of 20 years, with a mean value of 12 $\pm$ 3.9 years. The canopy area presented a minimum value of 0.8 m^2 and a maximum value of 70.9 m^2, with an average value of 4.19 $\pm$ 15.5 m^2.

Table 3. Data collected and calculated for selected samples.

Parcel	Tree nr.	h_t (m)	h_c (m)	h_{total} (m)	Canopy Diameter (m)	DCH (cm)	Trunk Weight (kg)	Branches Weight (kg)	Total Weight (kg)	Age (years)	Canopy Area (m^2)
1	3	17.3	6.3	23.6	1	10.25	52.5	2.1	54.6	10	0.8
1	5	10.46	4.9	15.36	1	6.9	23.6	5.2	28.8	5	0.8
1	6	10.35	2.85	13.2	2.1	8.45	29.7	3.8	33.5	14	3.5
1	8	16.2	6.7	22.9	9.5	30.7	578.9	15.9	594.8	20	70.9
1	16	12.93	5.54	18.47	2	8.05	45	2.8	47.8	10	3.1
1	17	8.3	3	11.3	2.5	5.5	14.2	4.3	18.5	9	4.9
1	19	14.2	3.7	17.9	4.3	14.9	145.8	21	166.8	12	14.5
1	26	13.8	3.5	17.3	1.2	17.05	223.6	25.5	249.1	14	1.1
1	27	5.8	3	8.8	1.2	4.2	43.5	3.1	46.6	10	1.1
1	29	6.8	3.1	9.9	1.8	4.45	3.6	1.9	5.5	6	2.5
1	30	13.75	9.93	23.68	1	8.35	43.5	2	45.5	9	0.8
1	31	19.6	7.8	27.4	4.8	18.05	267.4	15.5	282.9	16	18.1
1	33	17.75	5.6	23.35	3.8	16.7	205	18.9	223.9	14	11.3
1	37	16.8	3.3	20.1	4.4	15.9	202.3	8.9	211.2	17	15.2
2	9	15.4	4.53	19.93	3.4	14.6	131.2	7.7	138.9	15	9.1
2	10	12.1	3.6	15.7	1.9	9.65	38.9	1.8	40.7	10	2.8
2	11	9	3.5	12.5	1.9	4.55	11	2.6	13.6	9	2.8
2	15	21.7	11	32.7	2.65	21.8	301.7	31.7	333.4	17	5.5
2	21	7.75	2.5	10.25	3.2	5.8	15.6	4.1	19.7	12	8.0
2	30	17.2	4.3	21.5	2.7	21.9	173.9	19.4	193.3	15	5.7

3.2. Mathematical Model for Estimating the Amount of Biomass of A. dealbata

To determine the mathematical model, multiple linear regression was used to verify whether the area of the canopies can be used to estimate the amount of biomass in *A. dealbata* stands. The analysis resulted in a statistically significant model, defined by Equation (1):

$$[F(1,18) = 35.502;\ p < 0.001;\ R^2 = 0.645], \quad (1)$$

The canopies area of *A. dealbata* trees ($\beta = 0.815$; $t = 5.958$; $p < 0.001$) can be used as an estimator of the amount of biomass. Equation (2) describes this relationship:

$$y = b_0 + b_1 \cdot x_1, \quad (2)$$

That is, according to Equation (3):

$$W_{bio.est} = 65.753 + 7.858 \times area\_canopy, \quad (3)$$

The use of the t-Student test to compare the mean aboveground biomass weights of *A. dealbata* measured and the weights obtained by using Equation (3) and presented in Table 4, based on hypotheses H1 and H2, indicate that it should choose hypothesis H1, since $p > 0.05$:

H1. *There are no differences between the means of the variables.*

H2. *There are differences between the means of the variables.*

Table 4. Measured and estimated biomass quantities.

Measured Biomass Weight (kg)	Estimated Biomass Weight (kg)
54.6	71.9
288	71.9
33.5	93.0
594.8	622.7
47.8	90.4
18.5	104.3
166.8	179.9
249.1	74.6
46.6	74.6
5.5	85.7
45.5	71.9
282.9	207.9
223.9	154.9
211.2	185.2
138.9	137.1
40.7	88.0
13.6	88.0
333.4	109.1
19.7	129.0
193.3	110.7

Thus, on average, the estimated biomass weight of *A. dealbata* (West. = 150.42, SE = 27.148) is statistically similar to the measured *A. dealbata* biomass weight ($W_{measured}$ = 137.54, SE = 33.341), t(19) = −0.04, $p > 0.05$.

3.3. Application of the Mathematical Model to Estimate the Amount of Woody Biomass in A. dealbata Stands from the União de Freguesias de Cabeça e Vide (Seia, Portugal)

To validate the model, it was applied to determine the amount of available biomass of *A. dealbata* in the territory of the União de Freguesias de Cabeça e Vide. With this objective, the identification of all existing settlements in the territory and their delimitation was carried out in the first phase. For this purpose, satellite photography was used from the same date on which the samples were cut, which was October 2018. A total of 41 settlements of *A. dealbata* were identified, distributed as shown in the Figure 5.

With the areas determined through the delimitation of the *A. dealbata* stands, Table 5 was elaborated, where the calculation of the amount of available biomass was added, using Equation (3). Subsequently, and since it was verified that the woody biomass corresponds to 91% of the total weight of the cut trees, the weight of woody biomass available was determined, as this will be of interest for recovery. Afterwards, the amount of biomass per hectare was determined to be able to make a comparison with the data available in the bibliography and to validate the procedure.

As can be seen from the results presented, the *A. dealbata* stands have the capacity to provide 863.5 tons of biomass, distributed over 12 hectares of land, which corresponds to a production of approximately 72 t/hectare. This result is in line with the result presented by Nunes et al. (2020), where the authors describe a trial where they proceeded to cut the biomass of *A. dealbata* in two previously delimited hectares, with all the cut biomass being weighed, totaling 140 tons [18]. In other words, these authors refer to a production of 70 t/hectare, which were later transported to a biomass pellets production unit for recovery.

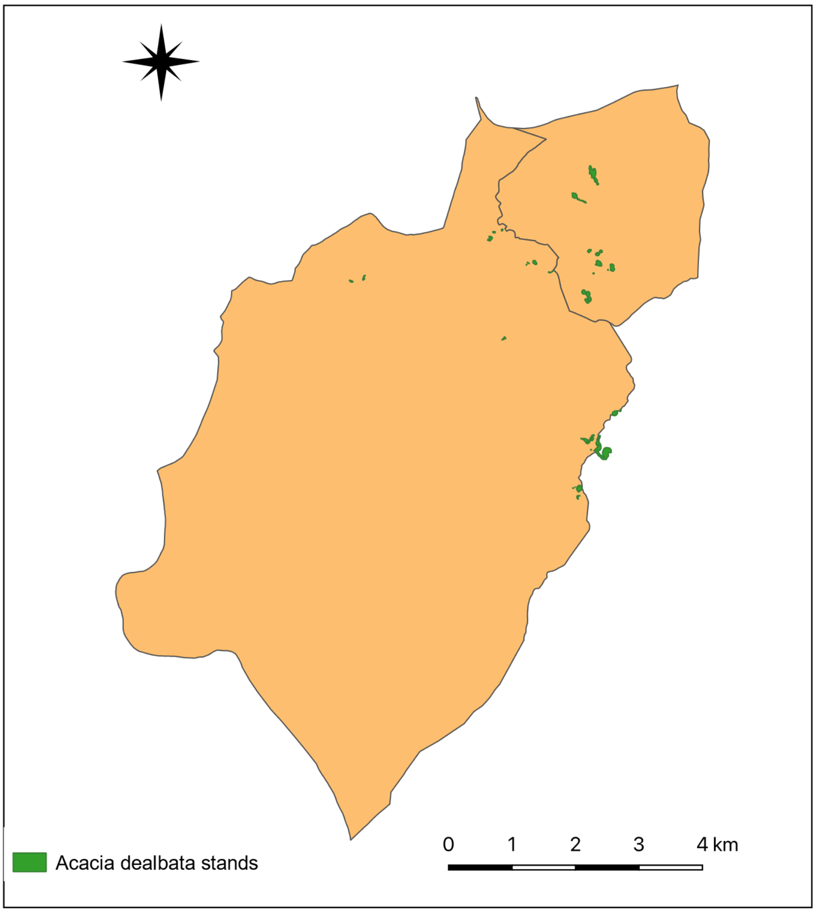

Figure 5. Distribution of *A. dealbata* settlements in the territory of the União de Freguesias de Cabeça e Vide.

Table 5. Area of settlements of *A. dealbata* existing in the territory of the União de Freguesias de Cabeça e Vide.

A. dealbata Stands	Area (m^2)	Aboveground Estimated Biomass (kg)	Aboveground Estimated Biomass (t)	Aboveground Estimated Woody Biomass (t)
1	1961.45	15,478.83	15	14.1
2	2331.7	18,388.25	18	16.7
3	5782.41	45,503.93	46	41.4
4	141.93	1181.04	1	1.1
5	5882.61	46,291.30	46	42.1
6	3701.94	29,155.60	29	26.5
7	3738.36	29,441.79	29	26.8
8	2884.44	22,731.68	23	20.7
9	2673.55	21,074.51	21	19.2
10	280.93	2273.30	2	2.1
11	2779.35	21,905.89	22	19.9
12	5087.1	40,040.18	40	36.4
13	1767.64	13,955.87	14	12.7
14	16,406.28	128,986.30	129	117.4
15	497.65	3976.29	4	3.6
16	138.68	1155.50	1	1.1
17	147.96	1228.42	1	1.1
18	100.73	857.29	1	0.8
19	82.05	710.50	1	0.6
20	1045.57	8281.84	8	7.5

Table 5. *Cont.*

A. dealbata Stands	Area (m^2)	Aboveground Estimated Biomass (kg)	Aboveground Estimated Biomass (t)	Aboveground Estimated Woody Biomass (t)
21	4985.52	39,241.97	39	35.7
22	644.61	5131.10	5	4.7
23	42.34	398.46	0	0.4
24	66.75	590.27	1	0.5
25	6016.9	47,346.55	47	43.1
26	131.66	1100.34	1	1.0
27	122.58	1028.99	1	0.9
28	33,364.1	262,240.85	262	238.6
29	5115.62	40,264.29	40	36.6
30	1360.39	10,755.70	11	9.8
31	1749.83	13,815.92	14	12.6
32	48.47	446.63	0	0.4
33	17.66	204.53	0	0.2
34	898.09	7122.94	7	6.5
35	25.57	266.68	0	0.2
36	1049.3	8311.15	8	7.6
37	1418.66	11,213.58	11	10.2
38	630.92	5023.52	5	4.6
39	830.72	6593.55	7	6.0
40	2943.09	23,192.55	23	21.1
41	1511.1	11,939.98	12	10.9

4. Discussion

Chemical control is, most likely, the most-used method in the control and eradication actions of *A. dealbata*. In fact, there are several references where examples of the use of the most diverse types of chemical compounds for the control of *A. dealbata* are found, namely those where the sensitivity of the species to different herbicide products is analyzed, as can be seen in the work of Delabraze & Valette [22], showing some efficacy of glyphosate, if used in high concentrations, as opposed to several other compounds, such as 2,4-D or fosamine-ammonium, which proved to be completely ineffective. This resistance of *A. dealbata* to chemical attack has led to the use of other processes, namely mechanical methods, such as cutting and peeling acacia trees.

However, any of these methodologies involve costs, both from the perspective of the acquisition of herbicides, as for the labor and means necessary for their application, and mechanical control methods, where it is also necessary to quantify the costs associated with labor and the mechanical means (motor-cutters, chainsaws, heavy equipment, trucks, among others) used in the works. Additionally, there is the need to repeat the actions until the eradication of *A. dealbata* in the area is complete. As previously mentioned, *A. dealbata* has a great capacity for recovery and resilience, being able to return, in a short period of time, to occupying the previously cleaned space. This is especially true if there is a seed bank in the soil, wherein they use the opportunity created by cleaning the vegetation cover so that they can germinate, enjoying direct access to sunlight, since it is a heliophile species. In other words, the control of this species is not limited to an occasional action of applying an herbicide or cutting down stands but rather requires the planning of a set of actions that necessarily have to extend over time, repeatedly, until that they do not germinate any more seeds or regrowth through roots and stumps.

Roughly, the costs associated with cutting a hectare of *A. dealbata* can be around the values shown in Table 6, which were obtained based on the information provided by ICNF (www.icnf.pt, accessed on 8 November 2021) for reference costs for forestry work.

Table 6. Forestry works reference costs map (adapted from www.icnf.pt, accessed on 8 November 2021).

Operation Action	Minimum Value (€/t)	Maximum Value (€/t)
Cut and branches cleaning	10.00	60.00
Retrieval and extraction	10.00	45.00
Transport with loading and unloading	12.00	60.00

The minimum and maximum values depend on the type of operation to be carried out and the conditions under which they are carried out. The important traits are the size of the area where the intervention takes place, the slope, whether heavy equipment is allowed, existence or not of accesses, and existence of other types of vegetation that require a more careful separation. Therefore, the values presented are only indicative of the costs that may be involved in the removal of *A. dealbata* biomass.

Currently, biomass considered residual may reach a value for energy recovery in power stations dedicated to biomass of approximately 15 €/t, placed at the destination. In other words, this value is practically used to transport the biomass to the recovery site, with the cost of cutting and returning it, normally, to be borne by the owner of the land that orders the service. In the case of creating a value chain, where prior planning is carried out, the destination of the biomass and the entire logistical scheme must be considered in order to optimize resources. It will be possible to achieve lower costs associated with operations, and the destinations can be optimized in looking for those that are able to pay more for biomass, such as the biomass pellet industry, domestic firewood users, or charcoal production units. In any of these production units, the purchase price of biomass can reach 35 €/t, depending on the diameter and quantities available for delivery, as consumers often want to have some regularity in raw material deliveries because it is a way to achieve greater homogeneity in the final product and, thus, ensure quality standards.

The biomass of *A. dealbata* has some parameters that can be problematic when used in large-scale combustion processes, as it has, for example, a higher chlorine content than other biomasses, such as *Pinus pinaster*, *Eucalyptus globulus*, or *Quercus* spp., traditionally used in the production of biomass pellets and used as firewood. However, as shown in the works by Nunes et al. (2020) or Nunes et al. (2021), this valorization is possible if the raw material is incorporated in a mixture that dilutes the parameter values that do not comply with the current quality requirements indicated by standards, such as ENPlus® for biomass pellets [18,23]. The creation of value chains can, in some way, contribute to the sustainability of control and eradication actions by allowing for some valorization of biomass while enabling the optimization of processes. This obligatorily reduces costs associated with control and eradication campaigns, increasing pressure on populations, which can be cyclically controlled until eradication.

However, although the applicability of the model presented here indicates good statistical significance, it is worth emphasizing that the model was built from data obtained from trees aged under 20 years. In other words, it is understood that the model can present a good statistical significance in stands younger than 20 years old, but that the same may not be accurate for stands of *A. dealbata* of older ages. This is because the growth of the tree crowns reaches an asymptote and stabilizes while, subsequently, the amount of biomass continues to grow, with the increase in the trunk and branches diameter. As in Portugal, the species of the genus *Acacia* are all part of the list of invasive species presented by Decree-Law no. 92/2019, of 10 July. *A. dealbata* is subjected to frequent control campaigns, and, because of this, it is challenging to find stands with old trees. For this reason, it is not easy to extrapolate the model to settlements of a different type from those found more frequently in Portugal without prior analysis of more data and different-aged stands. In any case, it is an expeditious procedure that can be used to optimize the control processes of the species by quantifying the biomass available in dense and single-species *A. dealbata* stands.

5. Conclusions

Invasive species are species that, not being native to a particular habitat, quickly become naturalized and compete very aggressively with native species, occupying their space and dominating the habitat. This occupation of habitats by invasive exotic species brings in a set of problems, such as the environmental issue, for example, associated with the loss of biodiversity and from an economic perspective, when it is associated with the loss of productivity of the planted forests used for raw materials. The control and eradication of these species is of particular importance, especially when, in a scenario of climate change such as the current one, the growth of these species increases the risk of fires, with Mediterranean-type climate regions being very susceptible to this situation. In Portugal, one of the species that has caused the most alarm is *A. dealbata*, which has occupied a prominent place at the top of forest species invasions. In this way, the development of policies and concerted interventions for its control has been a current practice. However, these actions, normally carried out using chemical and mechanical methods, require a certain temporal continuity, given the resilience of the species, resulting in high costs. For this reason, the creation of value chains for residual biomass resulting from control actions can be a way to contribute to the sustainability of these actions by allowing a reduction in financial losses, allowing the processes to continue to be carried out. This valorization will be more effective the more efficient its organization, planning, and optimization is, given the necessity of the development of expedite numerical tools that allow the quantification of the available biomass in the stands to be controlled so they can be properly programmed for their cut and forwarded to the best option for recovery. The tool presented here, despite some recognizable limitations that are closely associated with the data on the species that are currently available, seems, however, to allow the quantification of the biomass produced by *A. dealbata* stands using easily accessible information. However, since *A. dealbata* stands in Portugal are the target of frequent control actions, it is not possible to extrapolate the results to stands over 20 years of age since this was the maximum age found in the samples used to build the model. Therefore, so the data collection campaign should be continued to improve the model here presented.

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CHAPTER 5 – Assessment of the Impact on Forest Management Models, the Potential for Energy Recovery and the Provision of Ecosystem Services

Chapter Index

CHAPTER 5 – Assessment of the Impact on Forest Management Models, the Potential for Energy Recovery and the Provision of Ecosystem Services

Chapter Index

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Review

The Impact of Climate Change on Forest Development: A Sustainable Approach to Management Models Applied to Mediterranean-Type Climate Regions

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Abstract: Forest ecosystems are divided into three major groups: boreal, temperate, and tropical. These can be subdivided according to the particularities of each type due to its relative location (littoral, mountain, etc.), climatic conditions, or even geological substrate. Climate change affects each type of forest ecosystem differently. However, it seems to affect temperate forests in Mediterranean-type climate regions more intensely. These regions are located over several continents, with major impacts of increased temperature during summer and decreased precipitation during winter. This situation affects Mediterranean forest ecosystems by increasing the risk of fires, which arise more frequently and are more severe. In addition, the emergence of pests and the spread of invasive species are well-known problems affecting these ecosystems. All of these conditions contribute to losses of productivity and biodiversity. To avoid the destruction of forest resources, and since Mediterranean-type climate regions are considered climate change hot spots with increased vulnerability to disturbances, the implementation of adaptive forest management models could contribute to increasing the resilience of such forests, which could also contribute to mitigating climate change.

Keywords: climate change; forest ecosystems; sustainable forest management; Mediterranean forests

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1. Introduction

Climate change is considered the most significant challenge humanity has ever faced [1]. This perspective attaches great importance to the matter, leading to the launch of several global initiatives, with the intention to find solutions to mitigate the problem, specifically through paths that minimize the consequences [2]. The most visible and reported effect is undoubtedly the increasingly recurrent frequency with which extreme weather events occur, directly affecting the daily lives of people all over the world [3]. Example of this include the change in monsoon cycles, which subsequently changed agricultural cycles in Southeast Asia, significantly impacting food production, and prolonged drought periods in Mediterranean-type climate regions, with a direct impact on the increased risk of rural fires, as shown by recent events in California (USA), Portugal, Spain, and Greece, caused by the increasing air temperature in the Mediterranean-type climate regions, as shown in Figure 1 [4,5].

Forests are of particular importance as they are some of the most important ecosystems on the planet and are the habitats for an endless number of species. Table 1 shows the distribution of different types of forest ecosystems distributed by the respective climatic domains.

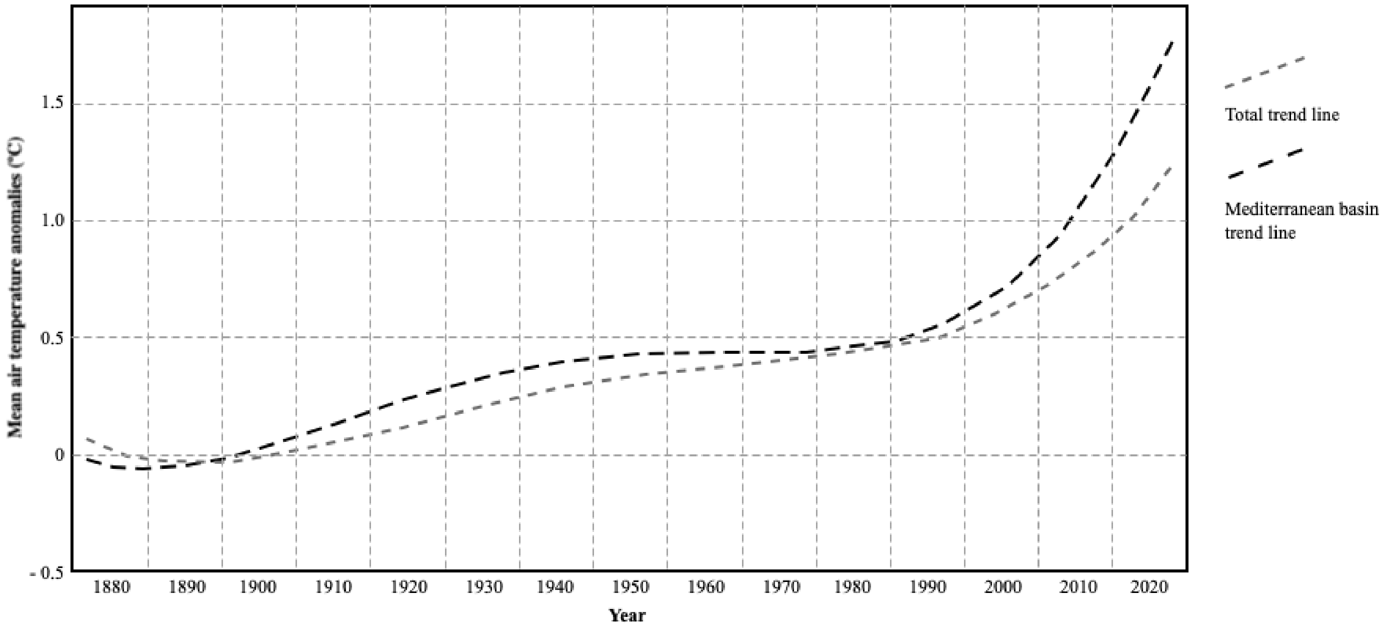

Figure 1. Temporal distribution of annual mean air temperature anomalies on the period 1880–1899 [6].

Table 1. Proportion of forest area by climatic domain in the year 2020 (adapted from https://www.cepf-eu.org/news/two-important-reports-published-worlds-forests, accessed on 22 December 2021).

Forest Type	Proportion (%)
Tropical	42
Boreal	27
Temperate	16
Subtropical	11

However, as this is a global-scale problem, with the capacity to change all biological, geological, physical, and chemical cycles of the entire Earth system, the impact on forests is also a reality, acting on these systems in a distinct but progressively way, altering the way forests evolve [7]. This evolution, as reported in several studies, presents a profound change in climatic parameters on a regional scale, causing changes in ecosystems and leading to, for example, the replacement of native species by exotic species, which, coming from regions presenting edaphoclimatic conditions closer to those observed now, may have higher competitive capacity, thus replacing native species in the ecosystem [8]. This leads to the loss of biodiversity, but it also causes damage to populations [9]. Such damage can be caused directly, for example, by the loss of productivity of a particular forest species, but also indirectly, by increased recurrence of rural fires, which in turn can accelerate the transformation of forest cover toward the development of pyrophytic species [10]. This type of replacement contributes even more to changing the type of forest, leading to the destruction of native forests and enhancing their replacement by exotic invasive species [11].

The adaptation of forests to new constraints because of climate change not only has an impact on aspects related to the stability of ecosystems, but also has a direct impact on populations living in and on the periphery of forest spaces. These alterations act as disturbances to ecosystems, such as the frequent occurrence of extreme heat events, which enhance the aridity of soils, and changes in rainfall, which make agricultural livelihoods more precarious, as indicated by Serdeczny et al. [12]. As those authors also indicate, the precariousness of rural systems can, in turn, lead to the growth of migratory movements originating in rural areas toward urban centers, leading to the growth of urban areas, with subsequent changes in land use. Contrary to what can be expected, forests located at higher latitudes may benefit from increased atmospheric carbon dioxide concentrations and rising temperatures, with expected significant increases in growth and wood production rates, at least in the short to medium term, as indicated by Lindner et al. [10]. On the other hand, increasingly frequent disturbances in the remaining forest regions of the planet will cause adverse effects that will be felt severely by people, with subsequent social impacts.

Thus, in the first part, this paper is aimed at analyzing the identified impacts of climate change on forests, namely those related to forest fires and invasive species dispersal, and in the second part, pays particular attention to forests located in regions with a Mediterranean-type climate. It is also aimed at understanding the impact of such evolution on the ecosystem services that these forests provide. Finally, it analyzes how forest management models can contribute to the sustainability of forest resources and which models can be more beneficial to counterbalance the impacts of climate change in forests in Mediterranean-type climate regions.

2. Forests in Mediterranean-Type Climate Regions

2.1. Mediterranean-Type Climate

The Mediterranean climate, or the Mediterranean-type climate when referring to regions not located in the Mediterranean basin, is characterized by rainy winters and dry summers. However, the apparent regularity has undergone visible changes in recent years associated with climate change, causing a reduction in precipitation during the winter, as mentioned by Tuel and Eltahir [13]. According to those authors, these regions stand out because of the magnitude and significance of the winter precipitation decline, with the reduction reaching up to 40% in some regions. This loss of precipitation could place profound limitations on water resources, which will constrain the capacity of regions to produce food, thus affecting populations that are often lacking in water, creating social instability. This recent acceleration of climate change accentuates the already frequent and profound environmental problems in Mediterranean-type climate regions caused by the combination of changes in land use, pollution, and loss of biodiversity [14]. Cramer et al. point out that in the coming decades, there will be a scenario of increased risk in strategic and vital areas with regard to the availability of water, preservation of ecosystems, food production, and population health and safety [6]. Due to their assumed importance, these questions require careful analysis, allowing the acquisition of in-depth knowledge about the climate and how it will evolve in each Mediterranean-type climate region.

Several studies have characterized the various changes observed in recent years in these regions. For example, Lionello and Scarascia [15] indicate that global temperatures have warmed, and decadal variability leads to significant uncertainty, preventing the identification of long-term links between precipitation and global temperature. On the other hand, Tramblay et al. [16], based on assumptions raised by other authors, developed a model to better understand the impact of global changes over a century. These changes necessitate serious consideration of the impact of climate change in different areas, particularly those that directly affect people's lives. Even though it is a type of climate with similar characteristics in all regions, the geographic distribution of these regions over different continents necessarily implies specificities inherent to each one, and even within regions, some differences must be taken into account. In this way, for the construction of forecasting models, the collection of temporal data series is assumed to be a handy tool on which climate evolution models can be built, which can later be used to predict the evolution of concrete situations, such as forest ecosystems. The adaptability of different species to climate change has been the subject of in-depth studies, such as the work developed by

Klausmeyer and Shaw [17], in which they analyze the potential for species in Mediterranean ecosystems worldwide to adapt to climate change, with an emphasis on habitat loss.

2.2. Mediterranean Forests

Mediterranean-type climate regions naturally present high biodiversity, which has attracted much attention in recent years, especially in terms of studying the effects of climate change. This biodiversity is the result of differential speciation and extinction rates during the Quaternary, which was influenced more by the incidence of fires and the severity of climate change than by environmental heterogeneity, according to Cowling et al. [18]. The authors also draw attention to the fact that all Mediterranean-type climate regions have many rare and locally endemic taxa where small populations survive, many of which are threatened by habitat transformation. This diversity seems to contribute to greater productivity of forests, as pointed out by Vilà et al. [19]. However, according to the same authors, functional group richness has increased wood production only in sclerophyllous forests. However, despite all of the biodiversity identified in these forests and the recognized high productivity, Mediterranean forests are very fragile and vulnerable to numerous threats such as fires, over-exploitation, deforestation, and degradation, which, according to Pahali et al., are currently being accentuated in the context of climate and land-use changes [20]. The permanent search for resources provided by Mediterranean forests serves to increase the value attributed to these resources, although, as pointed out by Croitoru [21], most of them are poorly recognized.

Currently, there are Mediterranean forests in five regions spread over several continents: in the Mediterranean basin, with forests distributed across various countries in Europe, Africa, and Asia; in California, North America; in Chile, South America; in South Africa, Africa; and in Australia, Oceania (Figure 2). Despite the broad geographic dispersion, all of these regions share a set of similarities, with increased aridity, mainly by decreased precipitation but also by higher temperatures, as the main threat to the diversity and survival of Mediterranean forests, as pointed out by Peñuelas et al. [22]. This weakness was previously recognized by several authors, such as Scarascia-Mugnozza et al. [14], who recommend the implementation of careful strategies for conservation and management. As those authors mentioned, this approach implies the need to identify appropriate silvicultural and management strategies, which will have significant effects on defining the criteria for sustainability and eco-certification. Issues of a social nature must also be considered as determining factors for effective forest conservation. Otherwise, it will be impossible to control forest fires and landscape degradation. Baeza et al. [23] highlight human action as the primary disturbance in the origin of fires and changes in land use, which play a critical role in the current state of vegetation. For example, fires create vegetation patches in different successional states, whereas land use and soil type define different shrubland types in terms of their specific composition [24].

2.3. Main Climate Change Disturbances in Mediterranean-Type Climate Regions

2.3.1. Framework

Despite climate change being a global phenomenon, the consequences of its manifesting all over the planet, mainly in the form of extreme weather events, are felt more intensely and severely in some specific regions. These consequences will generate a set of responses at different levels, as presented in Figure 3. Giorgi [25] called these regions climate change hot spots. The author developed the so-called Regional Climate Change Index (RCCI) based on regional mean precipitation change, mean surface air temperature change, and precipitation and interannual variability change. Using this index, a set of regions were identified as hot spots. Among all analyzed regions, the Mediterranean and northeastern Europe emerged as the primary hot spots, followed by high-latitude regions in the Northern Hemisphere, along with Central America, the most prominent tropical hot spot. Southern Equatorial Africa and the Sahara are the major African hot spots, and eastern North America is the most important hot spot on that continent. These projections were later confirmed by other authors, such as Georgi and Lionello [26], who again identified a robust and consistent picture of climate change over the Mediterranean, consisting of a pronounced decrease in precipitation, especially in the warmer season.

Figure 2. Location of the Mediterranean-type climate regions, which are distributed by Central Chile, California and Northern Baja California, Southwest and South Australia, Western Cape, South Africa, and the Mediterranean basin.

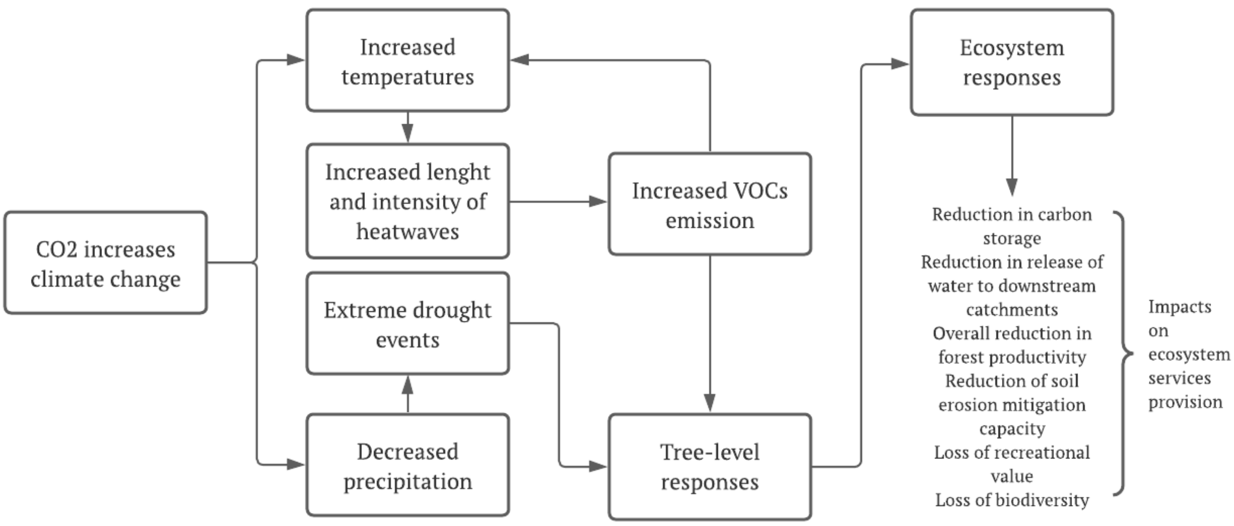

Figure 3. Tree- and ecosystem-level responses in Mediterranean forests to environmental changes associated with climate change and their impacts on ecosystem service (ES) provision [27].

Diffenbaugh et al. [28] looked beyond this evidence and analyzed the reasons for the intensification of climate change in Mediterranean regions, and concluded that higher greenhouse gas concentrations increase heat stress risk in these regions, with the occurrence of extreme heat increasing by 200% to 500%. The authors pointed out the preferential warming of the hot tail of the daily temperature distribution as the cause of intensified heat stress, with the 95th percentile maximum and minimum temperature magnitude increasing more than the 75th percentile magnitude. Following this work, Diffenbaugh and Giorgi [29] modelled different scenarios with varying temperature limits for different levels of global warming, and found that the Mediterranean region emerged as a prominent regional climate change hot spot in response to intermediate and high levels of forcing. This knowledge of possible scenarios can help to inform mitigation and adaptation decisions by quantifying the rate, magnitude, and causes of the aggregate climate response in different parts of the world.

It seems that the Mediterranean regions will undergo intense changes in their climate patterns, with several studies pointing in this direction. Lionello and Scarascia [15] analyzed the relationship between climate change in Mediterranean regions and global warming, and noted that during the 20th century, (i) Mediterranean and global temperatures warmed at a similar rate until the 1980s, and (ii) decadal variability led to large uncertainty preventing identification of long-term links between precipitation in the Mediterranean region and global temperature. However, the same authors presented a scenario for the 21st century in which the mean global temperature increases, and precipitation decreases, with warming felt more in summer and reduced precipitation occurring mainly in winter. The relationship between decreased precipitation and the subsequent increase in temperature is directly related to an increase in extreme drought phenomena, which in turn contributes to the occurrence of increasingly recurrent and severe fires.

2.3.2. Fire as a Shaping Agent of the Mediterranean Landscape

Five regions of the world share a similar climate and structurally identical plant communities. These five regions, known as Mediterranean-type climate regions, as described by Keeley [30], are dominated by evergreen sclerophyllous shrublands, semideciduous scrub, and woodlands. These vegetation types are prone to widespread crown fires, and the common drought periods in summer represent an annual fire hazard that contributes to a highly predictable fire regime. Fire plays an important role in the development of these systems, as reflected in plant traits such as lignotubers in resprouting shrubs and delayed reproduction, which restrict recruitment to a pulse of post-fire seedings. These species, when installed in fertile soil, can resprout very quickly in the post-fire period, and opportunities for post-fire seedling recruitment are limited. Thus, these woody rates did not evolve in the way of delaying reproduction, as indicated by Keeley. In a review addressing the effect of fire on Mediterranean climate ecosystems, the author states that this fire-independent mobilization is common to the flora in the regions of the Mediterranean basin and in California, whereas post-fire seeding is more frequent in more arid regions due to their own geological specificities, with soils that are very poor in nutrients; therefore, the post-fire resprouts do not present such competitive behavior to seedlings, as post-fire seeding is more common. In Chile, also described by Keeley, there seems to have been fire-prone landscapes in the Andean uplift in the Tertiary, which were lost during the Miocene, which now prevent summer lightning storms from reaching the region.

Currently, all of these regions encounter serious problems with fire management, caused by the increased risk of fire, especially during the hottest and driest season, but also by the amount of highly flammable vegetation that accumulates during the remaining seasons of the year. It is also important to note that periodic fires are an important natural process in Mediterranean-climate ecosystems (Figure 4). However, as mentioned by Syphard et al. [31], the increased recurrence of fires profoundly threatens the fragile ecological systems of these regions. They also address the issue of the origin of fires, pointing to human action as the main cause, and relate population density with their occurrence. They conclude that there are few instances of human ignition in areas with low population density; therefore, fire frequency is low. On the other hand, when population density increases, human ignition and fire frequency also increase, at least until a certain threshold is reached. A similar relationship was obtained by Nunes et al. [32], who analyzed the evolution of fires between 1975 and 2020 in a region of northern Portugal. The authors related the occurrence and distribution of fires, verifying that increased recurrence of fires is directly related to increased population density, especially in a system of territorial organization with population nuclei being dispersed and interspersed with forestry and agricultural spaces. The authors also refer to human action as the main cause of the occurrence of fires, similar to what was reported by Syphard et al. for California (USA); therefore, it can be assumed that it is most likely a cause that extends to all Mediterranean-type climate regions.

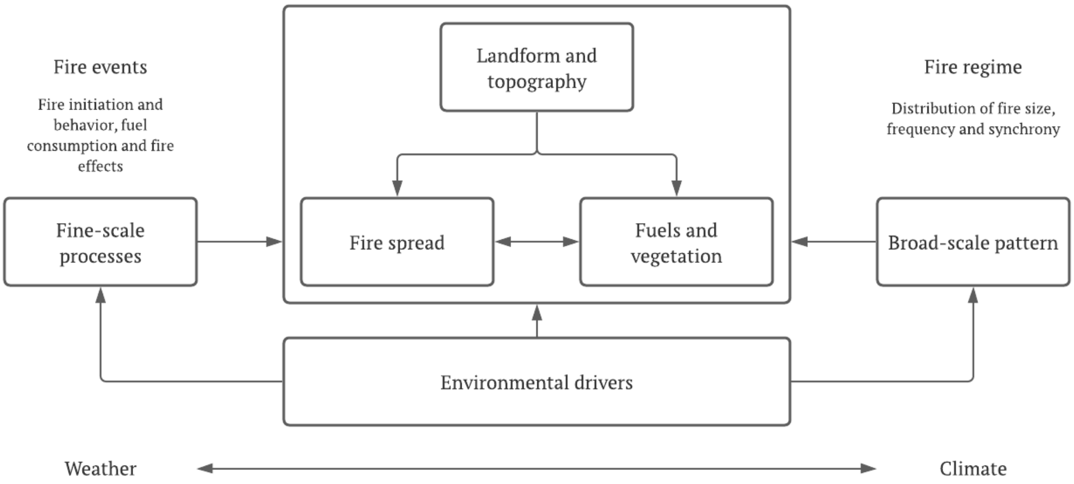

Figure 4. Cross-scale interactions of pattern and process in fire regimes. Environmental drivers of weather and climate, interacting with landform, set the overall template for individual fire events and fire regimes. Interactions between fire spread and vegetation determine the properties of fires at fine scales, while creating broad-scale landscape pattern [33].

2.3.3. Social and Economic Impacts of Climate Change on Mediterranean Forests

The forests that grow in regions with a Mediterranean climate and fall within the group of temperate forests have always been the object of exploitation by human populations, who learned to use the resources made available by forests [34]. In the regions surrounding the Mediterranean basin, this interaction reached levels of near symbiosis, with populations interacting with forests in such a way that shaped both and created agroforestry–pastoral systems, of which the "montado" in Portugal and the "dehesa" in Spain are examples [35,36]. In these areas, where the management activities of *Quercus suber* and *Quercus rotundifolia* forests are mixed with agricultural practices in dryland conditions, alongside the raising of animals (sheep, goats, cattle, and pigs), populations shaped the landscape over thousands of years, adapting it to their needs, but it also adapted itself to the available resources, which have always been managed sustainably [37]. This interaction between populations and the natural space (albeit partially artificialized) lead to the development of a culture that today identifies itself as Mediterranean, which, despite the differences that exist between the peoples of the Mediterranean basin, has commonalities to all, always related to the landscape that unifies them [38]. Figure 5 shows an example of the "montado" landscape.

After thousands of years of development of a culture supported by the territory from which it was born, in which traditional practices allowed populations to develop and prosper, profound changes in regional characteristics emerged and changed the way certain practices continue to develop [39]. In fact, all practices associated with the agroforestry-pastoral environment are dependent on the succession of seasons and the climatic conditions of these regions, which in turn led to the development of specific types of floristic associations. However, with climate change, these conditions have been profoundly altered, leading to variations in the productive cycles of the species, with increased temperature in the summer and reduced precipitation in the winter, along with other problems, such as the arrival of invasive exotic species that directly compete with native species [40].

Figure 5. "Montado" landscape in Southern Portugal, in the region of Alentejo with a forest of *Quercus suber*.

Fire, which has always been a part of Mediterranean ecosystems as an agent modelling the landscape and conditioning the evolution of the territory and the species that inhabit it, began to play a destructive role, contrary to what happened in the past when occurrences of fire spaced out in time contributed to the regeneration of crops and the elimination of pests and diseases [41]. Currently, with the changes in climatic parameters, fires have started to have a destructive role, with increased frequency and, mainly, in severity, with very significant impacts from an economic and social point of view [42]. The destruction of forest resources leads to the loss of a set of economic activities, including those of an industrial nature, such as cork production, but also traditional practices within the field of agriculture and pastoralism that also contribute to the income of rural populations [43]. This destruction of economic resources, in turn, leads to the emergence of problems and social disorder, through the elimination of jobs [44]. However, the social component is not just about the destruction of economic value, as the landscape component and people's enjoyment of natural spaces are also part of the well-being component, whether from the perspective of enjoyment of the people who live in the vicinity or the perspective of enhancing the landscape, for example, for tourism purposes, as is presented in Figure 6 [45].

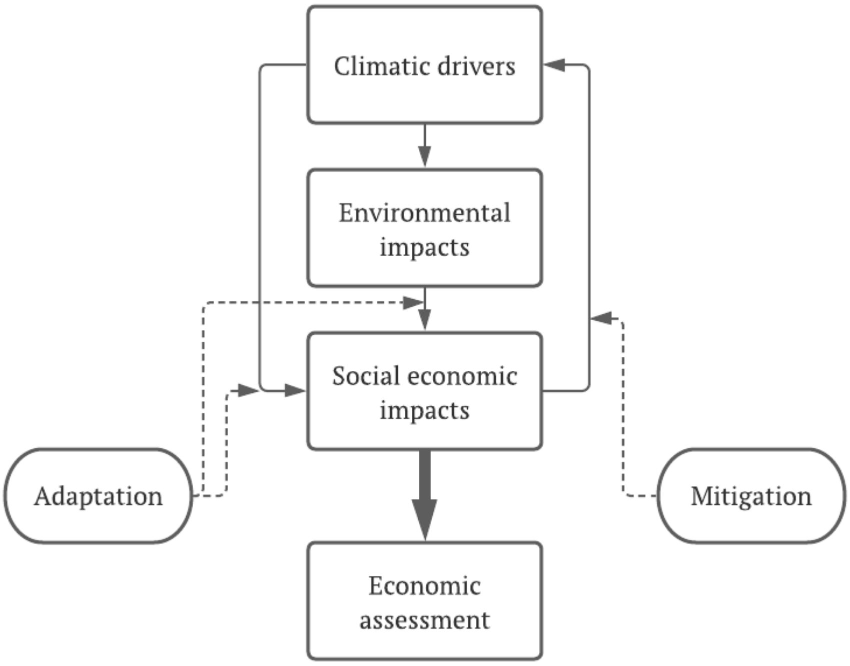

Figure 6. Socioeconomic impacts of climate change (adapted from https://www.iemed.org/publication/the-economic-impacts-of-climate-change-in-the-mediterranean/, accessed on 22 December 2021).

3. Forest Management in a Climate Change Scenario

Forest management in current times is forced to adapt to the new reality in a scenario of climate change, which implies major impacts and modifications in forest ecosystems. As previously mentioned in the work of Spittlehouse and Stewart [46], climate change is expected to have significant impacts on forest ecosystems over the next hundred years; therefore, surely practices associated with forest management must adjust to the new reality. It is increasingly expected that forest management will assume a position of contributing to the sustainability of resources, with an integrative vision that not only encompasses the traditional management of forest productivity as a supplier of raw materials, but also includes services that forests can provide, namely ecosystem services such as carbon capture and sequestration.

In the current scenario, which implies profound changes in climate parameters, with increased temperature and decreased precipitation, problems related to invasive species are added, which greatly contributes to uncontrolled growth and the accumulation of fuel load, which in turn significantly increases the risk of rural fires. In fact, as mentioned in the work by Seidl et al. [47], considering climatic uncertainties in management planning is a prerequisite for sustainable forest management, since it is also understandable that, as Linder [48] noted, projected climate change will strongly impact forest growth and composition, with obvious impacts on the exploration and enjoyment of forest resources. Spittlehouse [49], following this perspective, states that climatic change will affect society's capacity to profit from forest resources.

Based on the scenario in which climate changes lead to an expected increase in temperature, maintaining the structure and functions of Mediterranean forests has become a challenge for forest managers. Vila-Cabrera et al. [37] showed that research is focused mainly on strategies to decrease risk and promote resistance in the short term, rather than on enhancing long-term resistance. On the other hand, as expected in economic activities, management strategies seek to obtain benefits in the short term and frequently have unintended consequences on other adaptation objectives and untargeted ecosystem components that are so important in Mediterranean-type climate regions.

4. Discussion

Forest management presents a set of problems that are now enhanced by the impacts of climate change, namely changes in climate parameters such as temperature and precipitation, and other underlying problems, such as an increased risk of fires, the spread of invasive species, and the emergence of pests and diseases [50]. Although of a different nature, these problems have some points in common, as they all contribute to the loss of productivity in forests, the degradation of the natural space, the loss of ecosystem services provided by forests, and the loss of biodiversity [51]. In addition to these negative consequences, they also have a common point, as they are all directly and indirectly related to the impacts caused by climate change [52]. In fact, these problems have always been described in the literature; therefore, it can be considered that they have always existed as part of forest ecosystems [53]. However, especially in the last two decades, all of these problems intensified to such an extent that it is practically impossible for them to go unnoticed.

Taking as an example the occurrence of fires, there is growing recurrence all over the globe, even in locations where fires occur infrequently; they were frequent in Mediterranean-type climate regions such as Portugal, Australia, and California (USA), but the same cannot be said of Sweden and Alaska (USA) [54]. In other words, climate parameters such as average air temperature and precipitation are changing in such a way that regions where fires were less likely to occur are now also experiencing more fires [55]. As has been widely reported in the media around the world, these fires, even in boreal forest regions, reached very significant dimensions, which were previously not common [56]. On the other hand, in temperate and tropical regions, where fires have always been frequent, they are now reaching truly catastrophic proportions, remaining active for weeks or months, making it impossible for fire-fighting forces to extinguish or control them with the means available, with increasingly high costs, as shown in Table 2.

Table 2. Average annual fire suppression expenditure for the emergency fund of California Department of Forestry and Fire Protection (adapted from https://www.statista.com/chart/19807/california-wildfire-emergency-fund-expenditure, accessed on 22 December 2021).

Decade	Cost (USD)
1979–1989	25,000,000
1990–1999	61,000,000
2000–2009	236,000,000
2010–2019	401,000,000

However, the changes in temperature and precipitation are not only responsible for the intensification of and changes in patterns of occurrence of forest fires [57]. The changes in climatic parameters also interfere very significantly with the resilience of forest species, weakening them and making them more vulnerable to attacks by pests and diseases [58]. In this way, weakened forests will lose their competitive capacity, acquired during evolution over time in a given location and under certain edaphoclimatic conditions, due to the arrival of invasive species, many coming from regions with conditions identical to those that exist now [59]. This competition between native and exotic species usually leans on the side of newcomers, which are more aggressive, quickly occupying spaces in the ecosystem left empty by native species unable to adapt to new conditions [60]. In turn, these invasive species usually have the capacity to grow much faster than native species and are associated with a very large dispersal capacity, making them capable of accumulating large amounts of biomass that will also act as a fuel load to increase the risk of fires, creating a kind of vicious circle in which fire works as an agent of artificial selection and promotes and benefits pyrophyte and heliophile species [61]. In this way, the replacement of forest cover happens at the speed at which fires reach a certain region.

Forest management must assume the primary task of assessing the state of vulnerability of forests in the face of climate change as a starting point for the planning of management methodologies, but also include a review of expectations in terms of the use of forests, identifying needs at the level of research and education, developing forest policies to facilitate adaptation, and identifying the moment of implementation of responses, as described by Spittlehouse. Additionally, along this line of thought, Ogden and Innes [62] point out the need to articulate the specific objectives for adaptation to climate change, which the authors consider to be coincident with the criteria assumed for the conservation and sustainable management of forests. In a second stage, and because forest management plans are hierarchical (there are higher-level strategic plans and lower-level operational plans), it is important to distinguish which planning level is most appropriate to consider options.

On this assumption, and according to Bolte et al. [63], implementing an adaptive type of forest management can help forest ecosystems to adapt more easily to the new conditions so that the objectives of the management model are achieved while maintaining the ecosystem services and reducing the risk of forest degradation. As a management strategy, the authors presented (i) conservation of forest structures, (ii) active adaptation, and (iii) passive adaptation, with the criteria for applying each strategy depending on the intended management objective. For those authors, forest adaptation may entail the establishment of neonative forest, including the use and intermixing of native and non-native tree species, as well as trees with non-local provenance that may adapt better to future climate conditions, using an integrative concept of adaptive management that combines species suitability tests and modelling activities, priority mapping of adaptation strategies, and implementation. This approach to the concept of integrative adaptive forest management combines actions on different spatial scales based on their interaction regarding greenhouse gas mitigation and forest adaptation. In this way, actions that lead to forest adaptation at a local scale will have an influence on the success of global greenhouse gas mitigation, which will in turn contribute to triggering climate change and adaptation pressure at the local level, as shown schematically in Figure 7.

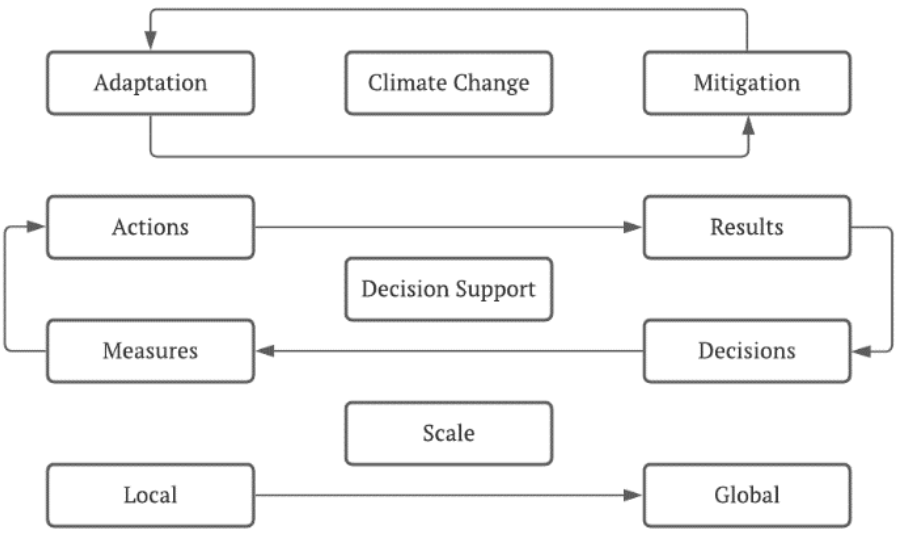

Figure 7. Integration concept of adaptive forest management [63].

The existence of so many interrelations and interdependencies within a forest ecosystem with high biodiversity such as the Mediterranean requires a holistic approach that encompasses the entire ecosystem, and does not focus solely on forest species, but also involves other species from all biological kingdoms. As Bolte et al. reported, research and planning efforts must be intensified to meet all information needs regarding the ecosystem under consideration, so that the adaptation of the forest system can be included in the overall adaptive land-use management model.

Planted forests will also suffer from the impacts of climate change, and the adaptation of forest management to the new reality requires knowledge of the effects of climate change on forests, associated industries, and communities [64]. Keenan [65] states that the prediction of how effects might change over time and how to incorporate this knowledge in management decisions depends on new approaches to forest management. This author points out that the most relevant themes that should receive particular attention are (i) predicting species and ecosystem responses to the future climate, (ii) adapting actions for forest management, (iii) developing new approaches and tools for decision-making under uncertainty, and (iv) making policy arrangements for adaptation in forest management. This adaptive capacity assumes particular importance, especially when it is expected that there will be significant impacts on forest ecosystems over the next hundred years, as described by Spittlehouse and Stewart [46], who pointed out the need to evaluate the long-term effects on forests, and thus determine what measures should be implemented now and in the future to respond to the threat.

Thus, the foreseeable impacts are not limited to the loss of productivity of forest resources or of biodiversity, or even ecosystem services, but could also include the capacity of forests as an economic resource. Forests are sources of raw materials and support many activities that contribute to the creation of income and wealth; therefore, they have high social impact. However, the destruction of activities such as hunting and the collection of wild fruits, mushrooms, and nuts, including destruction of the landscape itself, with direct impacts on tourism, can put the very livelihoods of rural populations at risk. This can cause serious social consequences, with the flight of these populations to cities, further enhancing the already complex problem of the organization of territories and the asymmetries between rural and urban populations. Combating climate change is, therefore, an urgent need, as only by implementing mitigation measures, including measures related to sustainable forest management, will it be possible to mitigate, in a first phase, and then reverse the catastrophic effects of radical climate change in the following stages, as presented in Figure 8.

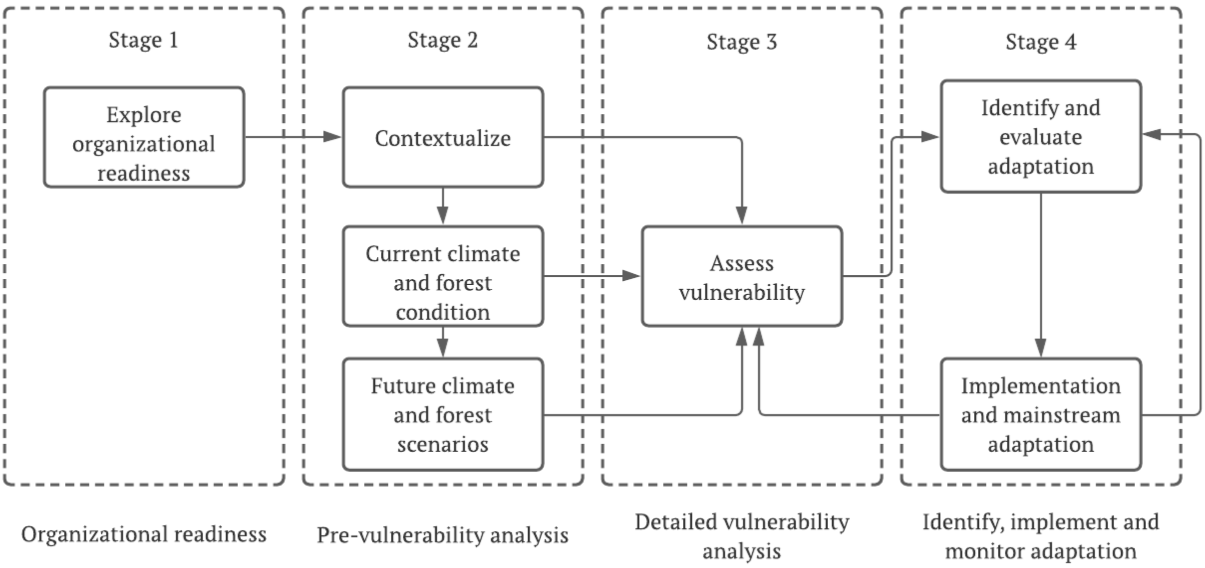

Figure 8. Four stages of adaptation to climate change in the context of sustainable forest management [66].

5. Conclusions

Climate change is a problem that affects everyone on a global scale, with a profound impact on ecosystems. Forest ecosystems are susceptible to climate change, and are affected in different ways, ranging from the loss of forest productivity to the loss of the ecosystem services they provide, such as the capture and sequestration of atmospheric carbon. Although all forests are affected by climate change, those in Mediterranean-type climate regions have greater susceptibility, derived from the effects of climate change on parameters such as temperature and precipitation. These parameters affect the development of forest species by weakening them, which potentiates the emergence of diseases and pests and invasive species, and an increased risk that even more intense and severe fires will occur. In this way, the implementation of adaptive forest management systems is presented as a need so that forests can become more resilient and able to adapt to the new reality, and, thus, also to contribute to climate change mitigation.

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CHAPTER 5 – Assessment of the Impact on Forest Management Models, the Potential for Energy Recovery and the Provision of Ecosystem Services

Chapter Index

environments

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Article

Control of Invasive Forest Species through the Creation of a Value Chain: *Acacia dealbata* Biomass Recovery

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Abstract: In Portugal, some species are now considered invasive by law and have proliferated in recent years. Among these, *Acacia dealbata* stands out. This work investigated the behavior of this species, in order to characterize and evaluate its potential as raw material for biomass pellets production, while controlling its proliferation. It was found that *A. dealbata* has a large capacity for raw material supply, as cutting 2 ha resulted in about 140 tons of biomass. Thus, the attribution of a market value for this material could result in a reduction in the area occupied by the invasive species, once the demand for it increases, causing a pressure over the resource. This pressure on the species must be duly followed by other control measures, such as reducing the population and mitigating its proliferation. Laboratory tests have shown that both the raw material and the finished product are similar to those obtained with other species normally used for biomass pellet production, such as *Pinus pinaster* and *Eucalyptus globulus*. Thus, it can be concluded that there is a high potential for this species in the production of biomass pellets for energy, and that this may be an important contribution to controlling the proliferation of this invasive species.

Keywords: *Acacia dealbata*; biomass energy; biomass pellets; invasive species; value chain

1. Introduction

Actually, the current situation created by the climate change scenario enhanced a set of phenomena that, somehow, affect the normal development of the natural environment, altering it, and conditioning its evolution [1–3]. In this way, these changes, which directly influence meteorological variables associated with climate, such as rainfall or insolation, will contribute to the alteration of the growth profiles of native species, harming them in detriment of others, exotic, that eventually can be more adapted to the new situation, and, for this reason, more able to react quickly, occupying the habitats [4–6]. The development of these alien species has a highly negative impact on biodiversity, jeopardizing the evolution of ecosystems in a natural way, enhancing the substitution of native species, often with a monoculture trend, reducing the number of species present in a given habitat [7–9].

Some species have the ability to adapt to new edaphoclimatic conditions and to acquire invasive behavior [10–12]. However, in the majority of the cases regarding the introduction of invasive species, the aim was to achieve some sort of commercial purpose, such as the massive production of a certain raw material, rather than through the mere ignorance of those who introduced them inadvertently [13–15]. This is often supported by a purely economic view of the forest, or the use of species to fulfill some indirect objective, such as the stabilization of roads and highway slopes or the lowering of groundwater levels, where attention is only paid to the intended remedy, not to the ecological and biological components of the method used [16–18]. In this perspective, *Acacia dealbata* presents itself as a problem in several regions of the planet, as shown by Nentwig et al. (2018) [19]. In Portugal there are also many references that can be found about the invasion by this species, where the dispersion processes, the effects on biodiversity, the impacts on the soil, or the behavior facing fire are reported [20–23].

It is also possible to find in the literature many examples of how the introduction of species occurred, such as the several situations described in the works presented by Lorenzo et al. (2010), Lorenzo et al. (2017), Lazzaro et al. (2014), or Lorenzo et al. (2012) with *A. dealbata* [24–27]. Another example that can be described, occurred in Portugal during the 1980s, when a rumor that an industrial unit for tannin extraction and concentration would be set up in Palmela, located near Setúbal, in southern Portugal, most likely to supply the growing wine industry of that time. With this information, many landowners in the nearby regions rushed to start planting *A. dealbata*, especially on the Pegões floodplains region. Over time and due to the failure of the industrial project, the population of *A. dealbata* grew and even began to expand to neighboring areas, creating a large area of monoculture that occupied thousands of hectares, as no other species was able to survive with such a high density of *A. dealbata* [18,28].

Almost 40 years later, and with the need to return the occupied land to other crops, notably for the cultivation of orchards, vineyards, and stone pine forests, landowners began a campaign for the eradication of *A. dealbata*. On a specific site, in a property called "Herdade de Santo Isidro", where a company occupies an area of approximately 40 ha, and which operates a forest species production garden, a project has been developed for the cutting and grubbing up from the roots the entire area. Taking advantage of this project, the available biomass per hectare was quantified, as well as its characterization for potential use as an energy resource, specifically for its viability for the production of biomass pellets.

There are already some works on the dispersion processes of *A. dealbata*, such as the works presented by Rodriguez et al. (2017), or the work presented by Lada et al. (2019) on the influence of climatic factors on growth and capacity to sequester CO_2, where *A. dealbata* is also analyzed. However, no specific growth model was found for *A. dealbata* populations outside the original habitats [29,30]. In this way, the present study appears as innovative, since it presents, although still in a preliminary way, an evaluation of the growth rates and the potential of generation of biomass of the species, since it allows the quantification of the potential of space occupation outside the habitats where the species originated. Similar studies have been carried out and presented previously, but always referring to the territories of origin, in Australia, where they frequently relate the growth and dispersion of acacias and their relationship with other species, namely their impact on animal communities, such as in the work presented by Trouvé et al. (2019) [31]. On the other hand, a study presented by Aguilera et al. (2015), deals with the shade tolerance of *A. dealbata* in Mediterranean forest ecosystems of South America, but only addresses the relationship between luminosity and species growth after germination [32]. In fact, the question of the cutting of acacias can, itself, contribute to the spread of the invasion, as described by Lorenzo et al. (2010), where cutting can boost regrowth, increasing the number of growing specimens that will, in the future, be responsible for the production of seeds [24]. This large number of seeds, which have the capacity to resist for long periods of time until conditions allow the germination, has been pointed out, for example in the work by Passos et al. (2017), as one of the main causes for being so difficult to control this species [33].

The objective of the present work was to characterize the exotic species *A. dealbata*, considered invasive in Portugal, regarding its potential as a raw material for the production of biomass pellets for energy. This characterization comprised four stages, distributed as follows:

- 1st Stage—laboratory characterization of the raw material;
- 2nd Stage—production of biomass pellets on a laboratory scale;
- 3rd Stage—production of biomass pellets on an industrial scale;
- 4th Stage—combustion tests.

2. Materials and Methods

2.1. Collection and Preparation of the Samples

For the realization of this study, 2 ha occupied exclusively by *A. dealbata* were selected, delimited, and cut. This delimitation was intended to quantify the total existing biomass per hectare. All the biomass was cut, baled, and then sent by truck (as shown in Figure 1) to an experimental wood pellets production unit located in the municipality of Oliveira de Azeméis (North Portugal). It is important to note that the distance between the point where the biomass was collected and the industrial unit where it was analyzed and processed is approximately 290 km. This distance is only acceptable because it is a test, since in a normal situation, similar to what happens with other forms of residual biomass, such as forest residues resulting from sanitary thinning operations in maritime pine forests, or the selection of poles in eucalyptus plantations, this biomass must be consumed locally. The issues related to biomass logistics are decisive for the viability of waste recovery projects, since the usual disadvantages such as the low density of materials, the low calorific value, and the high moisture content, make transport responsible for a significant part of the costs associated with the process [34]. Upon arrival at the industrial unit, the batches were inspected and weighed, and then unloaded at the raw material storage facility, where samples were randomly collected from all trucks transporting the biomass to the industrial unit. Ten trucks were used to transport a total of 140 tons.

Figure 1. The material was cut and baled in order to facilitate transport, but also to ensure that all the material collected on the ground was transported to the company for weighing, processing, and analysis.

The weight of the samples that were collected in the industrial unit storage park was approximately 5 kg per truck. These samples were later crushed and mixed to homogenize the sample. Then, the materials were characterized in the laboratory and later pelletized on a laboratory scale, before moving on to the industrial scale production test. In this sampling process, all the constituent parts of the plant were collected, namely trunks with bark, branches, and leaves, since, given the young age of the plants to be cut, the separation of the different constituent parts would be impossible.

2.2. Laboratory Analysis

2.2.1. Chlorine Content

Chlorine is usually present in biomass in low concentrations; however, during combustion, chlorine acid is formed, which can lead to corrosion in the furnace. Therefore, it is crucial to determine the torrefaction temperature that eliminates this component. Chloride titration was the method chosen to determine the chlorine content, and the equipment used was a Titrator 7000 from SI Analytics. The sample preparation involved the digestion of the sample, performed in a MDS-6G microwave from Sineo, as the titration requires a liquid sample.

This method consists of measuring the potential difference, while the titrant, in this case, $AgNO_3$, is added. Equation (1) presents the redox reaction that occurs. Following titration, the software creates a spreadsheet with the potential difference and titrant volume variation over time. The first derivative can then be calculated through Equation (2), and consequently, the equivalence point can be determined as the volume corresponding to the maximum of the first derivative.

$$Cl^{-}(aq.) + AgNO_3(aq.) \rightarrow AgCl(s) + NO_3^{-}(aq\,.) \quad (1)$$

$$f'(x) = \frac{\Delta U}{\Delta V} = \frac{U_i - U_{i-1}}{V_1 - V_{i-1}} \quad (2)$$

where ΔU is the potential difference variation in mV, and ΔV is the volume variation in mL. The chlorine content on a dry basis is then determined by Equation (3), in compliance with the standard EN15289.

$$W_{Cl,\,db}(\%) = \frac{(C - C_0)\times V}{m} \times 100 \times \frac{100}{100 - M_{ad}} \quad (3)$$

where C is the concentration of the chloride in the solution in mg/L, C_0 is the concentration of chloride in the blank solution in mg/L, V is the volume of the solution in L, m is the mass of the test portion used in the digestion in mg, and M_{ad} is the moisture content in the analysis test sample in %.

2.2.2. Major and Minor Elements

Inductively coupled plasma optical emission spectrometry (ICP-OES) is an analytical technique, that produces excited atoms and ions that emit electromagnetic radiation at different wavelengths for the determination of trace elements. The main advantages are its multielement capability, broad dynamic range, and effective background correction. For the preparation of the samples, microwave digestion was necessary to ensure that the capillaries did not become obstructed.

The model used for the sample analysis was the iCAP 6000 series from Thermo Scientific. A peristaltic bomb delivers the digested samples to an analytical nebulizer, which is then introduced into the plasma flame. The sample is broken down into charged ions and eventually gives off radiation at the characteristic wavelengths of the elements involved. In the end, the software of the device generates a spreadsheet with all the results. Equations (4) and (5) were used to calculate the content of each element in the sample on a dry basis to guarantee compliance with the standards EN15289, EN15290, and EN15297.

$$w_{i,db}(mg/kg) = \frac{(C_i - C_{i,0})\times V}{m} \times \frac{100}{100 - M_{ad}} \quad (4)$$

$$w_{S,db}(\%) = \frac{(C - C_0)\times V}{m} \times 0.3338 \times 100 \times \frac{100}{100 - M_{ad}} \quad (5)$$

where, for Equation (4), C_i is the concentration of the element in the diluted sample digest in mg/L, $C_{i,0}$ is the concentration of the element in the solution of the blank experiment in mg/L, V is the volume of the diluted sample digest solution in mL, m is the mass of the test portion used in g, and M_{ad} is the moisture content in the analysis test sample in %; and where, for Equation (5), C_i is the concentration of the sulphate in the solution in mg/L, $C_{i,0}$ is the concentration of the sulphate in the solution of the blank experiment in mg/L, V is the volume of the diluted sample digest solution in mL, m is the mass of the test portion used in g, 0.3338 is the stoichiometric ratio of the relative molar masses of sulfur and sulphate, and M_{ad} is the moisture content in the analysis test sample in %.

2.2.3. Elemental Analysis

The elemental analysis was performed in a Leco CHN628 Carbon/Hydrogen/Nitrogen analyzer. The operation principle consists of weighing a sample into a tin foil that is later placed in the autoloader. The sample is then introduced to the primary furnace containing pure oxygen, which results in fast and complete combustion.

The carbon, hydrogen, and nitrogen present in the sample are oxidized to carbon dioxide (CO_2), water (H_2O), and NO_x, respectively, and are swept by the oxygen carrier gas through into a secondary furnace for further oxidation and particulate removal. The detection of H_2O and CO_2 occurs through separate optimized non-dispersive infrared cells, while the NO_x gases are reduced to N. Lastly, N_2 is detected when the gas passes through a thermal conductivity cell. After the analysis is complete, the moisture content obtained through the thermogravimetric analysis is introduced into the software, and the carbon, hydrogen, and nitrogen contents are automatically calculated. Following that, it is possible to estimate the oxygen content on a dry basis ($w_{O,db}$) from Equation (6).

$$w_{O,db}(\%) = 100 - w_{C,db} - w_{H,db} - w_{N,db} - w_{S,db} - w_{Cl,db} \tag{6}$$

where $w_{C,db}$ is the carbon content on a dry basis in %, $w_{H,db}$ is the hydrogen content on a dry basis in %, $w_{N,db}$ is the nitrogen content on a dry basis in %, $w_{S,db}$ is the sulfur content on a dry basis in %, and $w_{Cl,db}$ is the chlorine content on a dry basis in %. This procedure is in compliance with the standard EN 15104.

2.2.4. Proximate Analysis

Proximate analysis by thermogravimetry enables the study of the mass loss of the sample, in a controlled environment, as a function of the temperature. The thermogravimetric analyzer used during this project was the Eltra Thermostep model. One gram of each sample is introduced into crucibles and placed inside the oven, along with an empty reference crucible. As the temperature rises, the crucibles are weighed on a precision scale. Moisture, volatiles, and fixed carbon content are determined in this order throughout the heating process. Lastly, the final residue represents the ash content.

2.2.5. Heating Value

The heating value, also known as the calorific value, defines the energy content of biomass fuel. This parameter can be described in two ways: The higher heating value (HHV), or gross calorific value, refers to the heat released from the fuel combustion along with the vaporization energy from the water; and the lower heating value (LHV), or net calorific value, is based on steam as the product, which means its vaporization energy is not considered as heat. The heating value of biomass, both higher and lower, can be determined experimentally by employing an adiabatic bomb calorimeter. The model used in this project was the 6400 Automatic Calorimeter from Parr Instrument.

After each procedure, the equipment provides the corrected temperature rise which is later used for the determination of the heating value. As a result of the nitrogen and oxygen rich atmosphere inside the calorimeter, nitric and sulfuric acid are formed, respectively, and the heat from the formation of both acids must be disregarded. For the HNO_3, the wash water for the pump was titrated with NaOH 0.1 M, and Equation (7) was applied; while for the H_2SO_4, the knowledge of the sulfur content is enough to utilize Equation (8).

$$Q_{N,S} = 1.43 \times V_{NaOH} \tag{7}$$

where $Q_{N,S}$ is the heat contribution relative to nitric acid formation in calories, and V_{NaOH} is the volume of NaOH spent in the titration of the wash water of the pump in mL.

$$Q_{S,add} = 13.61 \times w_{S,db} \tag{8}$$

where $Q_{S,add}$ is the additional contribution relative to sulfur dioxide formation in calories, and $w_{S,db}$ is the sulfur content on a dry basis in %. Following this, Equation (9) can be applied to obtain the gross calorific value at constant volume ($q_{V,gr}$) in J/g.

$$q_{V,gr} = \left(\frac{\varepsilon \times \theta - Q_{thread} - Q_{N,S}}{m} - Q_{S,add}\right) \times 4.1868 \tag{9}$$

where ε is the calorific capacity of the calorimeter (previously determined) in cal/°C, θ is the corrected temperature rise in °C, Q_{thread} is the heat contribution relative to the thread combustion in calories, $Q_{N,S}$ is the heat contribution relative to nitric acid formation in calories, $Q_{S,add}$ is the additional contribution relative to sulfur dioxide formation in cal, and *m* is the mass of the sample in g. Equation (10) is used to calculate the gross calorific value at constant volume on a dry basis ($q_{V,gr,db}$) in J/g.

$$q_{V,gr,\Delta b} = q_{V,gr} \times \frac{100}{100 - M_{ad}} \tag{10}$$

where $q_{V,gr,db}$ is the gross calorific value at a constant volume in J/g, and M_{ad} is the moisture content in the analysis test sample in %. Net calorific value at constant pressure on a dry basis ($q_{p,net,db}$) in J/g can be calculated through Equation (11).

$$q_{p,net,db} = q_{V,gr,db} - 212.2 \times w_{H,\Delta b} - 0.8 \times \left(w_{O,db} + w_{N,db}\right) \tag{11}$$

where $q_{V,gr,db}$ is the gross calorific value at a constant volume on a dry basis in J/g, $w_{H,db}$ is the hydrogen content on a dry basis in %, $w_{O,db}$ is the oxygen content on a dry basis in %, and $w_{N,db}$ is the nitrogen content on a dry basis in %. It should be noted that the oxygen content used in Equation (11) is not the same as the one calculated in Equation (6). According to EN14918, ($w_{O,db}$ + $w_{N,db}$) is obtained from Equation (12).

$$\left(w_{O,db} + w_{N,db}\right) = 100 - w_{A,db} - w_{C,db} - w_{H,db} - w_{S,db}, \tag{12}$$

where $w_{A,db}$ is the ash content on a dry basis in %, $w_{C,db}$ is the carbon content on a dry basis in %, $w_{H,db}$ is the hydrogen content on a dry basis in %, and $w_{S,db}$ is the sulfur content on a dry basis in %.

2.2.6. Ash Fusibility Test

Ash samples were prepared by igniting biomass samples in a muffle furnace at 550 °C (BS EN 14775). The digestion of the ashes was performed in a microwave oven with H_2O_2, HNO_3 and HF in a heating ramp. Subsequently, acids were neutralized with H_3BO_3 and heated again. After the ash digestion procedure, the determination of the major elements was achieved with an ICP-OES instrument (iCAP 6000 Series—Thermo Scientific, Waltham, MA, USA).

Ash fusibility was examined with imaging sintering point-testing equipment (Sylab–IF2000-G) and the measurements were carried out following ISO 540 and ASTM D1857. Ash samples for the fusibility test were obtained by igniting the biomass in a muffle furnace at 550 °C, then shaping it into cylinders. Ash fusion temperature measurements were performed with a maximum temperature of 1500 °C, in the presence of an oxidizing atmosphere. Throughout the testing process, the different phases of the ash fusibility (initial deformation temperature—IDT; softening temperature—ST; hemisphere temperature—HT; and fluid temperature—FT) were recorded according to the shapes of the ash.

2.3. Laboratorial Scale Pellet Production

In the second stage, pellets were produced using laboratory scale equipment, and the density, humidity, lower heating value (LHV), and ash content were characterized. Figure 2 shows the sequence of the biomass preparation tasks, with the homogenization phase of the previously ground material, which later went on to the pelletization phase. In this process, as previously mentioned, all parts of the plant were used, namely, bark, branches, and leaves.

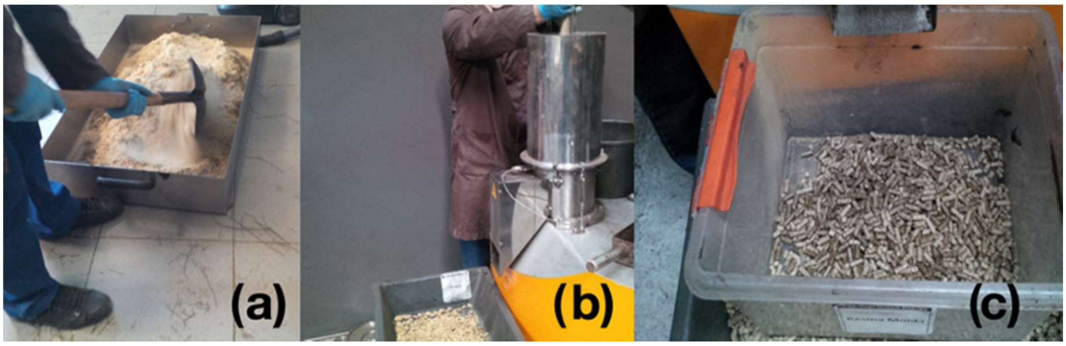

Figure 2. Pellet production process using a KAHL laboratory scale pelletizing machine with a production capacity of 25 kg/h. (**a**) The mixing process for homogenizing the product to be pelletized, mainly to ensure that the humidity is uniform; (**b**) the equipment used to produce the pellets; (**c**) the final result. The pellets were produced exclusively with *Acacia dealbata* biomass.

2.4. Industrial Scale Pellet Production

In the production test of biomass pellets on an industrial scale, a line with a production capacity of 1200 kg/h was used. It is a conventional line, with two stages of fine grinding, being a wet grinding and a dry grinding, that is, before and after drying the material, with the objective of fixing the maximum particle size < 6 mm, with the d_{50} being 3.15 mm. The material was dried to reach a moisture content of approximately 10–12%. The pelletizer used in the test was a Lameccanica machine, with a horizontal axis ring die, with two rollers. Subsequently, the produced pellets were cooled using a water-cooled double-walled screw conveyor and bagged. Figure 3 shows the equipment used in pelletizing and the product already bagged.

Figure 3. The production of pellets in industrial scale test. (**a**) The equipment used in the test: a LaMeccanica pelletizer with a production of 1200 kg/h; and (**b**) the produced pellets bagged and ready to be consumed in domestic equipment.

2.5. Combustion Test

In the fourth stage, about 50 tons of these pellets were consumed in a biomass industrial boiler to assess the fuel efficiency, while the remainder were bagged in 15 kg packages, as previously presented in Figure 3b, and used in household equipment to verify its quality as a fuel. This verification of the quality of the pellets was, in this work, made through the comparison with the consumption that the users had of conventional biomass pellets, bought in the market as being produced only with *Pinus pinaster* wood (maritime pine). In this comparative study, the collaboration of an industrial pine resin processing unit was requested in order to obtain data on high-performance equipment.

The collaboration of 20 domestic users was also requested, who used the *A. dealbata* pellets in domestic boilers and stoves. In all situations, the users indicated similarity in the consumptions obtained with the pellets of *A. dealbata*, in comparison with the consumptions that were verified with the previously used pellets, of maritime pine wood.

3. Results

3.1. Laboratory Analysis

The results obtained in the laboratory analysis of the biomass samples of *A. dealbata* are shown in Table 1.

Table 1. Results obtained in the laboratory analysis.

Laboratory Analysis	Parameter	Result
Elemental analysis CHN (%, db) (EN 15104)	C	48.2
	H	5.79
	N	0.314
Chlorine content (%, db)	Cl	0.04
Element content (%, db) (Sample digestion for ICP based on EN 15105, EN 15289, EN 15290, and EN 15297)	Al	3.44
	Ba	0.27
	Ca	55.6
	Cd	0.002
	Co	0.003
	Cr	0.02
	Cu	0.04
	Fe	1.44
	K	16.1
	Mg	7.08
	Mn	0.69
	Na	3.90
	Ni	0.01
	Pb	0.03
	Zn	0.49
	As *	-
	Si	10.9
	P *	-
	S *	-
	Ti *	~
Thermogravimetric analysis (%, db)	Ashes (EN 14775)	0.663
	Volatiles (EN 15148)	79.745
	Fixed carbon (by calculation)	19.563
	Moisture (EN 14774-3)	0.646
Heating value (MJ/kg, db) (EN 14918)	High Heating Value (HHV)	19.297
	Low Heating Value (LHV)	18.032
Ash fusibility test (°C) (CEN/TS 15370-1, in reducing atmosphere)	Initial deformation temperature (IDT)	662
	Softening temperature (ST)	1270
	Hemisphere temperature (HT)	1292
	Fluid temperature (FT)	1320

* The contents of As, P, S, and Ti presented values below the detection limit (% < 0.001).

3.2. Laboratorial Scale Pellet Production

The results obtained in the laboratory analysis of *A. dealbata* biomass pellets produced using a laboratory scale equipment are shown in Table 2.

Table 2. Characterization of the density, moisture, lower heating value (LHV), and ashes of lab scale pellets as received.

Parameter	Result
LHV (MJ/kg, ar)	16.95
Bulk density (kg/m^3, ar)	>600
Moisture (%, ar)	8–10
Ashes (%, ar)	<1

3.3. Industrial Scale Pellet Production

In the third stage, and after satisfactory results were obtained in the two previous phases, the 140 tons received were processed in an industrial scale test, producing 75 tons of pellets (Figure 3). This indicates a very good conversion rate as compared to the rate normally obtained from the conversion of pinewood, which is 2 tons of raw material for 1 ton of finished product; while with *A. dealbata*, the conversion rate was 1.87 tons of raw material for 1 ton of finished product. This more favorable conversion rate, which presented an average value of 1.83 tons of raw material, for 1 ton of final product, has to do with the fact that this species has a high drying rate after cutting. That is, during the time that mediates cutting, baling packaging, forming the loader and transporting it to the industrial unit to produce pellets, moisture loss can drop from the initial 50% to average values within the range 38–42%. In addition to this aspect of the productive yield, there was also a greater ease in the pelletization process, verified through the amperage reached by the densification equipment, which presented values about 15% below those verified for the pelletization of maritime pine and eucalyptus, indicating a lower energy consumption per mass unit produced. Another aspect observed during the pelletizing process was less wear on the parts where this phenomenon usually occurs, namely on the roller shells and on the pellet mill die.

3.4. Combustion Test

In this test, *A. dealbata* pellets were used in an industrial boiler for heating thermal oil, replacing pellets produced exclusively with maritime pine, as is presented in Figure 4. The compared parameters were the quantity of pellets consumed, the average temperature of the furnace, and the average temperature of the thermal oil during the same period of operation of the boiler. After the test it was found that the parameters referring to the average temperature of the furnace and the average temperature of the thermal oil were similar to those verified during the use of pellets produced with maritime pine, being, respectively, 568 and 195 °C. Regarding the quantities consumed, there was an increase of approximately 5% in the same period of work, which is in line with the difference in LHV between the pellets produced with *A. dealbata* and with maritime pine, as can be seen in Table 3.

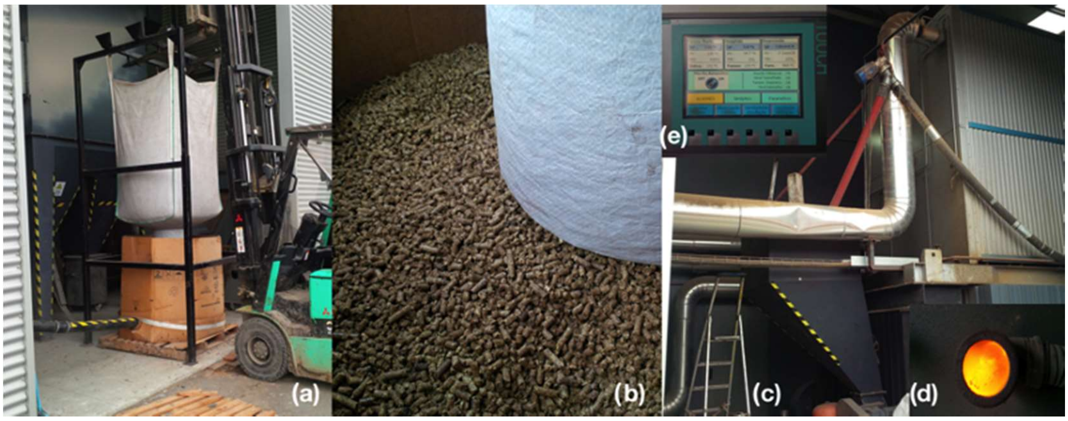

Figure 4. Combustion test of the pellets in an industrial thermal oil boiler. (**a**) The discharge of a pellet big bag into the boiler feed system; (**b**) the detail of the pellet discharge; (**c**) the boiler where the test was conducted; (**d**) the detail of the "eye" of the furnace in full combustion; and (**e**) the boiler control unit and the operating parameters.

Table 3. Comparison between the properties of the *A. dealbata* biomass and the reference values presented in the ENPlus standard.

Properties	Units	Enplus-A1	*P. Pinaster*	*E. Globulus*	*A. Dealbata*
Length	mm	3.15–35	3.15–35	3.15–35	3.15–35
Diameter	mm	6–8	6–8	6–8	6
Bulk density	kg/m^3	≥600	≥600	≥600	≥600
Moisture	%	≤10	≤10	≤10	8–10
Durability	%	≥97.5	≥97.5	≥97.5	≥97.5
Ash	%	<0.7	0.603	1.236	0.663
Volatile	% (db)	—	79.55	79.85	79.75
Fixed carbon	% (db)	—	19.85	17.41	19.56
Carbon	% (db)	—	56.4	52.70	48.2
Hydrogen	% (db)	—	5.85	5.82	5.79
Nitrogen	% (db)	≥0.3	0.138	0.166	0.314
Oxygen	% (db)	—	37.61	41.31	45.70
Sulphur	% (db)	≤0.03	≤0.01	≤0.01	≤0.01
Chlorine	% (db)	≤0.02	0.01	0.02	0.04
LHV	MJ/kg (db)	16.5 ≤ LHV ≤ 19	18.36	17.56	16.95

Combustion tests carried out by the 20 volunteers, who agreed to use the biomass pellets of *A. dealbata*, returned the information of total satisfaction with the product, without any report of problems during the use.

4. Discussion

As mentioned in the introductory section, climate change has decisively affected the development of forest cover in many regions of the planet, for example, causing changes in hydrological cycles [35]. These changes in the hydrological cycle cause long periods of drought in many regions, and this lack of precipitation increases the risk of rural fires, which in turn, by destroying the forest cover composed of native species, opens the way for invasive species, many of them pyrophytes [36,37]. In addition to the issue associated with the occurrence of rural fires, there is also the possibility of the occurrence of diseases and pests, which can also contribute to the weakening and death of native species, opening spaces where invasive species can take advantage of with their heliophile character, as described in the work of Boyd et al. (2013) [38].

This capacity that these invasive species have to dominate the space very quickly, creates a greater need to find ways that allow its eradication. However, several studies, such as the presented by Baker et al. (2017) or Forsyth et al. (2018), indicate that in most cases, eradication is not possible [39,40], or else it is extremely costly, as presented in the works of Epanchin-Niell (2017), Jardine and Sanchirico (2018) or Ngorima and Shackleton (2019) [41–43]. Thus, the control of these species presents itself as an unequal struggle, where failure can only be countered by maintaining their populations at levels that do not compromise native biodiversity, knowing in advance that the costs associated with control will always be very high. For this reason, related to the financial costs associated with the control of invasive species, the possibility of valorizing the collected biomass in some way, will allow to minimize the costs of the process, allowing its continuity and even its intensification, with the perspective of obtaining the best possible results.

It remains, however, an issue that must be raised, since the possibility of creating a value chain that justifies the collection of *A. dealbata* biomass, and that values it as a raw material for production of biomass pellets, may lead to the temptation, due to its rapid growth and potential for the supply of biomass, to be considered an energy culture and to be disseminated intentionally. In any case, in Portugal, the classification of invasive species and the ban on their dissemination has been legally prohibited since 1999, through Decree-Law No. 565/99, of 21 December, which was revised in 2019, and replaced by Decree-Law Law No. 92/2019, of 10 July, implementing one of the measures provided for in the National Strategy for the Conservation of Nature and Biodiversity for 2030 (ENCNB 2030), while allowing full implementation in the national legal system to the regime established by the Regulation (EU) Nr. 1143/2014, of the European Parliament and of the Council, of 22 October 2014, on the prevention and management of the introduction and spread of invasive alien species, so that the impossibility of any type of use of *A. dealbata* as a culture is guarded, which is not the result of control operations.

It is also important, when considering the possibility of creating a chain that values the biomass resulting from the collection of *A. dealbata*, that a growth model of the species is found, in order to be able to quantify the available quantities in an expeditious manner and assess the feasibility of creating the value chain. In the situation reported here, the land had been cleaned two years earlier. At the time of cutting for this test, the height of the trees, which can be measured when the bales are formed, of which an example is shown in Figure 1, is within the range of 2–6 m, while the diameters (DCH-Diameter at Chest Height) vary between 2 and 8 cm. Anyway, as mentioned, it is important to estimate the potential of a given region, in order to be able to assess the feasibility of creating a carbon neutral value chain. Tools already exist, based on satellite images or aerial and 3D data, that allow mapping the distribution of acacias that, based on data such as the size of plants and soil cover, are also able to determine the available quantities, but also, by georeferencing their location, they allow the optimization of collection routes, often reconciling with other forest products, such as maritime pine or eucalyptus. This optimization is important, since it can contribute to the reduction of logistical costs associated with the species control process. The works by Viana et al. (2010a), Martins et al. (2016), or Monteiro et al. (2017) present a set of works on discussing the potential to map acacias based on the coverage or height of plants using satellite [44–46]. The work of Große-Stoltenberg et al. (2018) presents the use of aerial and 3D data for the same purpose [47].

The quantities of biomass available in Portugal for energy have already been quantified in the work of Viana et al. (2010b). This work consisted of forest cover classification and mapping, and in the estimation of the available forest biomass and annual growth at national and regional levels, which allowed the evaluation of the geographical location of existing power plants, and the relationship between existing biomass and the power plants wood-fuel demand was examined with the application of a GIS-based analysis [48]. It is important to relate these data presented by Viana et al. (2010b) with the work of Vaz et al. (2017), since biomass is an important ecosystem service provided by the invader, since, like other species, it also contributes to carbon capture and sequestration, provides shelter for animal species, protects the soil from erosion, among others [49]. However, invasion by *A. dealbata* can also have a negative effect on the growth of populations of other species, such as the maritime pine, as described by Rascher et al. (2011), since in forest systems where water is scarcer, competition between species will favorably pend on *A. dealbata*, limiting the growth of maritime pine, reducing its productivity [50].

Regarding the creation of a chain that values the biomass of *A. dealbata*, there are several possibilities, for example, as mentioned in the example presented in the introductory section, the fact that *A. dealbata* is rich in tannins, which can be a renewable bioproduct, but which can prevent decomposition and is therefore not favorable for a scenario in which recovery is carried out using composting [51–53]. For this reason, the use of the biomass collected as raw material for the production of biomass pellets, presents itself as a promising alternative, since it can even be included in the collection networks already implemented for other species, optimizing the logistical operations.

From the tests carried out, results were obtained that indicate the use of the biomass of *A. dealbata* for the production of pellets and its use in everything similar to what already happens with other more conventional forms of biomass, namely the maritime pine or eucalyptus. As can be seen in Table 3, where a comparison is made between the reference values of the ENPlus standard, only the value for the chlorine content is above that indicated, being about twice the reference value of the standard. In this perspective, only the maritime pine falls within the reference values, since eucalyptus also presents values above 0.02%. In other words, since it is not possible to certify pellets produced only with *A. dealbata*, it is possible to incorporate the biomass of this exotic and invasive species, together with biomass, for example, from maritime pine. This incorporation may allow the creation of a value chain that justifies the collection of this form of biomass, contributing financially to the control of the species, while creating pressure on the resource, preventing its dispersion and proliferation.

The same table also presents indicative values for the characterization of maritime pine and eucalyptus. As can be seen, the values presented by *A. dealbata* are similar to those presented by the other two species, with a difference for the chlorine content, which is higher than that presented by the maritime pine, but equivalent to that presented by eucalyptus. There is also a small difference with respect to LHV, but it falls within the values of the ENPlus standard. This small difference may indicate a slight increase in the consumption of these pellets produced with *A. dealbata*, compared to pellets produced with maritime pine and eucalyptus.

Regarding the production process, it was found that the material is much easier to pellet than the biomasses normally used in this industrial unit. This is most likely due to the fact that *A. dealbata* presents values for the lignin content slightly higher than those found for maritime pine, 34% for *A. dealbata* and approximately 25% for maritime pine, respectively [54–59].

5. Conclusions

It was found in this study that *A. dealbata* has a large capacity for biomass supply. This was proven by the amount obtained in the test, with the cutting of the 2 ha resulting in approximately 140 tons of material. These results indicate its potential as a valuable raw material for biomass supply.

Laboratory tests showed that both the raw material and the finished product are similar to those obtained from *P. pinaster*, another species commonly used in Portugal for pellet production; that is except for the chlorine content, which was 0.04%, whereas the content normally obtained for resinous species is less than 0.02%. Thus, it was concluded in this study that there is a high potential for this species in the production of biomass pellets for energy. However, this is a purely indicative result, since the quantity supplied to each of the participants in the test, being the domestic or the industrial end users, did not allowed a prolonged use, and the results were only the communication of satisfaction, the type of equipment used, and if the consumption was similar that previously, when wood pellets produced with other raw materials were used, namely *P. pinaster* biomass.

Despite the positive results, it cannot be forgotten that *A. dealbata* is an invasive species, and that even if a value chain is created around this source of biomass, the objective should be only to contribute to reducing the costs associated with its eradication and control.

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CHAPTER 5 – Assessment of the Impact on Forest Management Models, the Potential for Energy Recovery and the Provision of Ecosystem Services

Chapter Index

resources

Article

Carbon Sequestration Potential of Forest Invasive Species: A Case Study with *Acacia dealbata* Link

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Abstract: Biological invasions are of complex solution, consuming resources for their control and eradication. However, in many of the documented processes that are available, this is an attempt with no solution in sight. The possibility of increasing the pressure over these species while creating value chains has been presented as a method for ensuring the sustainability of their control and eradication processes. In the case of invasive forest species in Portugal, such as *Acacia dealbata* Link, this control is becoming increasingly important. In addition to the negative impacts on biodiversity, the proliferation of this species has economic implications due to its competition with forest production species such as *Pinus pinaster* Aiton and *Eucalyptus globulus* Labill. Another critical aspect to be considered is the increase of the risk of rural fires, which is enhanced by the accumulation of low-value biomass around production forests. In this work, the possibility of using this species as a vehicle for the capture and sequestration of carbon in the medium and long-term was evaluated from a perspective of providing ecosystem services as a measure to mitigate climate change. However, due to its highly heliophilous character, it was found that the growth capacity of this species is rapidly conditioned by the position of each tree within a stand, not being able to maintain that capacity in the medium and long term.

Keywords: *Acacia dealbata*; energy recovery; carbon capture and sequestration; annual rate of carbon sequestration (ARCS); ecosystem services

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1. Introduction

Invasive forest species pose a permanent threat to the biodiversity of ecosystems, competing directly with native species for access to nutrients, water, space, and access to sunlight [1]. Due to their resilient nature, these species can override native species, gaining area, often taking advantage of external occurrences such as rural fires, since many of these species are pyrophytes [2]. This characteristic, which allows these species to benefit from rural fires, is easily explained if associated with another characteristic, mainly being heliophiles [3]. After being activated by the passage of the fire, which eliminates the vegetation cover, seeds can germinate without the competition of the shade caused by other plants, allowing access to sunlight and, thus, developing quickly [4]. Additionally to this germinative explosion, some plants may still sprout, depending on the fire severity, since roots often remain alive and can restart the growth process [5].

However, this competition for resources between exotic and native species does not affect only the biodiversity of natural ecosystems [6]. The invasion by exotic forest-type species has a direct and negative impact on production forests. These production species are used for a specific purpose, regardless of being exotic or not, and will suffer direct competition from these invasive species if their occurrence is not controlled by the forest managers [7]. For example, a production forest dedicated to eucalyptus for the pulp and paper industry can suffer from an acacia infestation, especially in the neighboring areas or in the areas of recent cuts, where acacias can have access to the sunlight, water, and soil nutrients. After being installed, the presence of these species can affect the productivity of other species with their allelopathic behavior [8]. Many examples of this competition are described and found in the available literature [9–11].

In Portugal, biological invasions have been studied for a long time and has been the subject of many studies [12]. In these studies are described several approaches, from the characterization of the occurrences, to the analysis of the biological cycles, or even to their control by diverse methods [13]. However, the invasion by forest species, in recent years, acquired an unusual role, being associated with the occurrence of rural fires [14].

This resilience, associated with the increased probability of rural fires and to the shortening of the occurrence periods, as a direct cause of the climatic changes in the regions of Mediterranean climate, has been identified as the most significant factor that contributes to the dispersion of invasive forest species, such as those of the genus *Acacia* [15]. In Portugal, despite several species of this genus already being registered, such as *Acacia melanoxylon* R. Br., *Acacia longifolia* (Andrews) Willd., and *Acacia saligna* (Labill.) H.L. Wendl., the one that has covered the largest area is *Acacia dealbata* Link. [16]. This species has increasingly developed in recent years, with a growth line beginning to trend upward, as shown in Figure 1. The area occupied until 1975 did not exceed 2500 ha. However, in the mid-1980s, the area occupied by *A. dealbata* started to increase. A relation can be found between the increase in the *A. dealbata* area and the number of events of rural fires. From the analysis of the historical data of rural fires, the tendency is toward a decrease in the number of events in the immediately following years, most likely due to the elimination of the fuel load and because it corresponds to the biomass recovering period. However, a deeper analysis may indicate a decrease in this recovery time of the aboveground biomass, especially if this type of species, such as *A. dealbata*, starts to be dominant in certain areas, increasing the risk of incidence of rural fires.

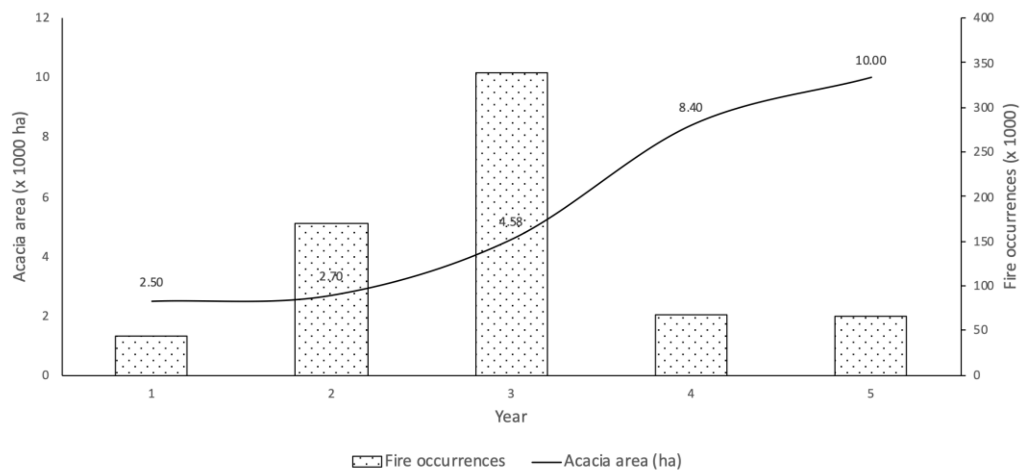

Figure 1. Increase in the area occupied by *A. dealbata* and its relationship with the number of occurrences of rural fires (adapted from [17–19]). The value of the occupied area for 2020 is only indicative, following a growth trend inflected in 2015, curbing a trend that pointed toward exponentiality, most likely due to the control measures implemented in many parts of the country.

A. dealbata, another species of the genus *Acacia*, and other forest-type invasive species are most likely undergoing a naturalization process, becoming adapted to the edaphoclimatic conditions of the area over time [20]. This naturalization implies that eradicating these species is becoming a long process given the inability to counter the germination rate of seeds already existing in the soil [21]. For different reasons, the same already happened with other species, such as *Eucalyptus globulus* Labill., which today thrives throughout the national territory in productive, planted forests and in spontaneous stands, which are currently part of the landscape [22].

While being a concern, these species such as *A. dealbata* become part of ecosystems, with adaptations of both ecosystems and the species to the new situation, leading to the organization of forest space and the services it provides [23,24]. Ecosystem services shall be reconsidered to include these species and the positive role they may eventually play since the negative impacts are already widely recognized [25]. Aspects such as biomass production for wood and fuels (wood pellets, charcoal, torrefied biomass, and chips, among others) lead to constant pressure on the now-defined resource, contributing to the control of its expansion, reducing negative impacts. Simultaneously, creating these value chains directly contributes to the minimization of the costs of control operations, giving some sustainability to the process [26].

Invasive species can contribute positively in other ways, for example, through carbon sequestration, contributing to the mitigation of climate change [27]. Species such as *A. dealbata* can play an essential role in capturing and fixing carbon since it is a fast-growing species capable of quickly removing significant amounts of carbon from the atmosphere in the form of CO_2 [28]. The creation of a sequence of operations including the control of invasive species that lead to a process of carbon concentration, such as carbonization or any other thermochemical conversion process, with subsequent sequestration of these materials in soils or landfills created for the purpose, falls under the classification of negative emission technologies (NET), according to the 2018 Special Report on the impacts of 1.5 °C global warming by the Intergovernmental Panel on Climate Change (IPCC) [29].

The objective of this investigation was to analyze the potential for carbon sequestration by *A. dealbata* through the evaluation of the total carbon content by elemental analysis (CHN) from a perspective of the possible provision of an ecosystem service by part of a species that is already part of the national landscape, for which the attempts to control and eradicate have been unsuccessful. After determining the average amount of carbon present in the species, the amount of equivalent sequestered carbon dioxide was calculated. By determining the age of the samples collected by dendrometric analysis, the annual productivity of *A. dealbata* in the study region was achieved. Based on these results, the CO_2 capture potential for 25 years was projected to analyze the carbon storage potential of the species.

2. Materials and Methods

2.1. Location and A. dealbata Sampling

For the collection of samples of A. dealbata, was selected Serra da Estrela, more precisely, the parish of União de Freguesias de Vide e Cabeça in the municipality of Seia, as shown in Figure 2. The selection was due to its location in the Serra da Estrela Natural Park, a sensitive area that needs care because it is a protected area, where A. dealbata is proliferating due to the recurrence of rural fires. As presented in Figure 3, several rural fires have overlapped during the last two decades, with several large fires occurring in the study area. As shown, almost the entire territory of the União de Freguesias de Vide e Cabeça has been affected by rural fires.

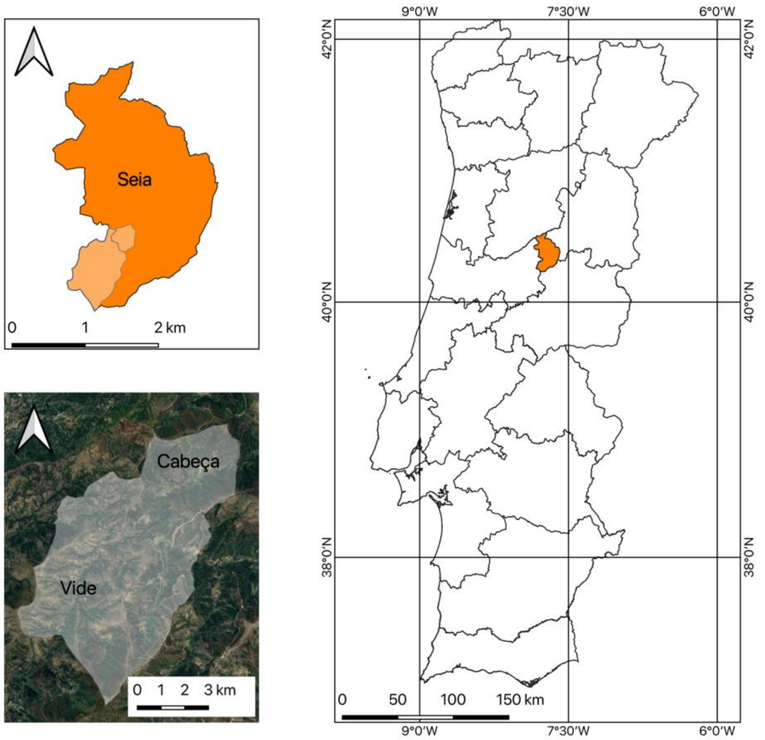

Figure 2. Location of the area under study where the samples of *A. dealbata* were collected.

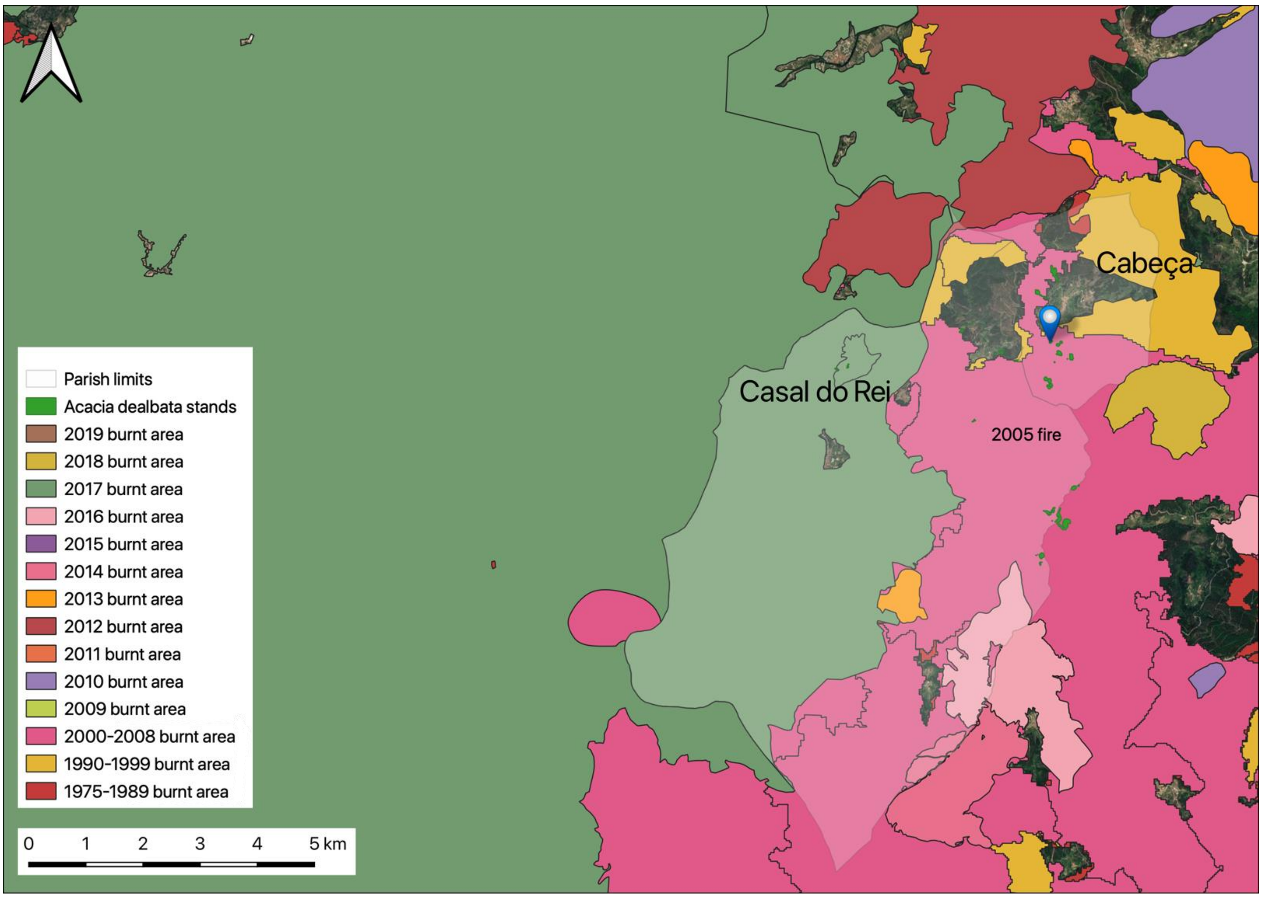

Figure 3. Overlapping occurrences of rural fires during the past two decades in the parish of União de Freguesias de Vide e Cabeça (Seia, Portugal).

Using open-source geographic information system (GIS) software, QGIS Version 3.16.4 LTR (Chicago, IL, USA), the zones occupied with *A. dealbata* were delimited and the areas estimated. The stand under study is located on the opposite slope of the Ribeira de Loriga valley to the road that connects the village of Casal do Rei to Cabeça, on a hillside that suffered a severe rural fire in 2005. In the post-fire period, *A. dealbata* gained area, expanding and multiplying the number of stands in the surroundings, as presented in Figure 4.

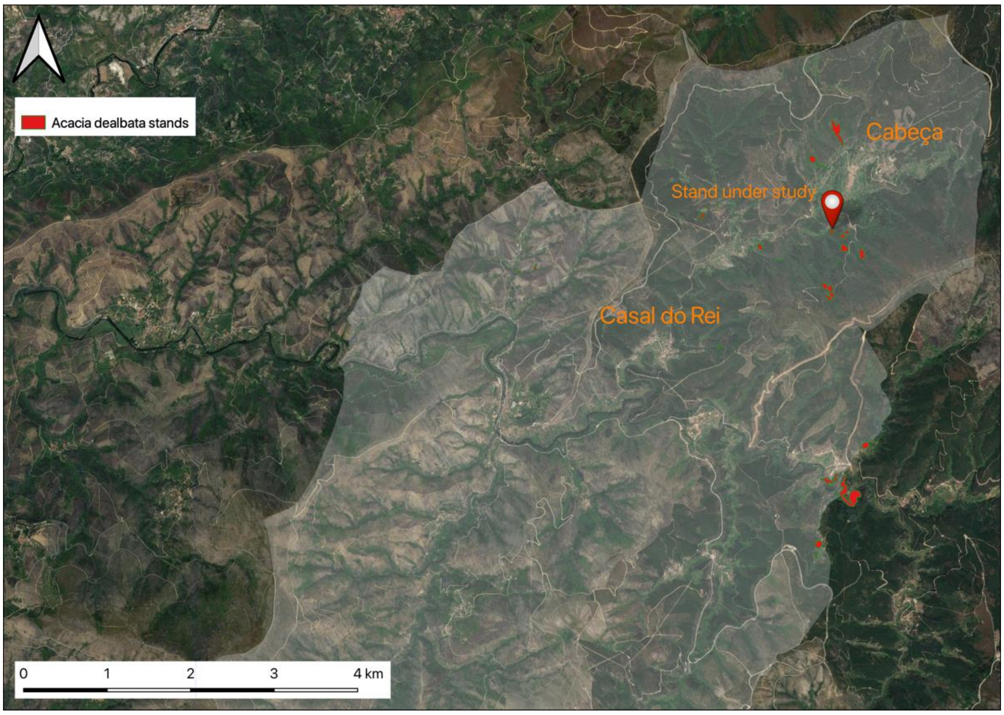

Figure 4. Identification of *A. dealbata* stands (marked in red) in the parish of União de Freguesias de Vide e Cabeça.

Figure 5 shows the areas obtained for the stand selected for this study. This selection was made based on accessibility criteria since the terrain is highly winding with very steep slopes, and pedestrian paths are practically nonexistent. The selected area has approximately 1962 m^2, within which a sub-area was around 710 m^2, corresponding to a circumference with a radius of 15 m. Subsequently, all trees within this circular zone were identified, and their diameters at breast height (DBHs) were measured. Then, DBHs were distributed by diameter classes: <5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35, and 35–40 cm. This distribution was used to select the trees to be cut for weighing and to measure the total height; the total weight is the sum of the partial weights of the trunk and branches with foliage, and the total height is the sum of the trunk and crown heights. After the selection of the representative elements for each diameter classes, the trees were cut, weighed, and measured as described. A parallel to the ground slice was cut and used to achieve the age of the sample. Only three specimens other than *Acacia dealbata* were found within this circular area: a specimen of *P. pinaster* and two specimens of *Arbutus unedo* L., supporting the idea that it is challenging for other species to develop inside dense acacia stands.

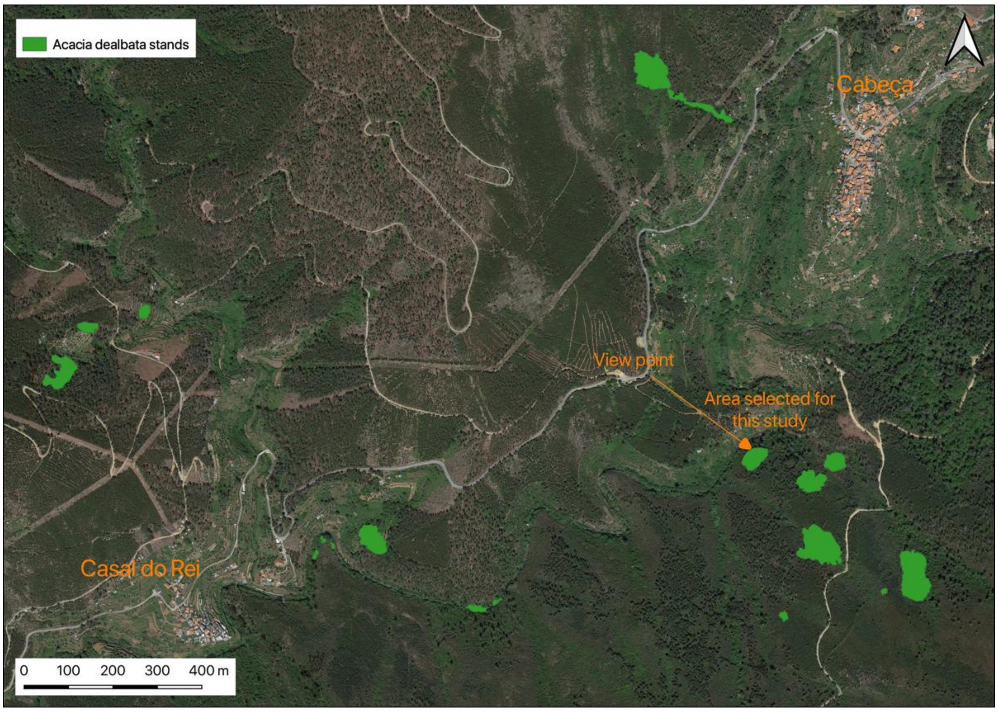

Figure 5. Delimitation and area measurement of the area under study where the samples were collected for elemental and dendrometric analysis.

2.2. Dendrometric Analysis

A slice of all the selected trees was cut and distributed to the appropriate DBH category as mentioned above. The samples, cut with a chainsaw, presented many irregularities on the surface, making counting the growth rings difficult. For this reason, they were subjected to an initial sanding to regularize the surface. After, were polished with coarse abrasive sandpaper and finished with fine abrasive sandpaper for a glossy polishing to facilitate observation. Later, the samples were scanned using an HP COLOR LASERJET MFP M477 fdw multifunction printer. The images scanned were treated using the open-source software ImageJ, and the growth rings were counted.

2.3. Elemental Analysis

To determine the carbon content, a LECO CHN628 elemental analyzer was used, according to the procedure described in ISO 16948: 2015-Solid biofuels—Determination of total content of carbon, hydrogen, and nitrogen.

2.4. Determination of the Total Amount of Carbon Weight and Annual Rate of Carbon Storage

The total amount of carbon storage by a tree can be achieved following the methodology presented by Clark III et al. (1986) and updated by Toochi (2018), which is based on the percentage of total carbon and the moisture content of the tree at the time of cutting [30,31]. This methodology is based on four stages and was adapted here as follows:

- Step 1: Determination of the wet weight of aerial biomass

  The wet weight was determined using the procedures described in Section 2.3.

- Step 2: Determination of the dry weight of the tree

  The dry weight of the tree ($dw_{aboveground}$) was determined by removing the percentage corresponding to the humidity to the total weight.

$$dw_{aboveground}\ (kg) = (100 - moisture) \times w_{aboveground}. \tag{1}$$

- Step 3: Determination of the carbon weight of the tree

The carbon weight of the tree was determined by multiplying the carbon content with the dry weight of the tree.

$$w_{carbon}\ (kg) = C\ (\%) \times dw_{aboveground} \tag{2}$$

- Step 4: Determination of the amount of CO_2 sequestered in the tree

The amount of CO_2 sequestered during the life of the tree is calculated based on the atomic weights of carbon and oxygen, which are, respectively, 12 and 16. The amount of CO_2 in the trees is determined by the ratio between the molecular weight of CO_2 and the atomic weight of carbon, that is, $(12 + 2 \times 16)/12 = 3.67$. So, to determine the amount and CO_2 sequestered by the tree, the calculation is:

$$w_{CO2}\ (kg) = 3.67 \times w_{carbon}. \tag{3}$$

- Step 5: Determination of the average amount of CO_2 sequestration

The amount of CO_2 sequestered annually is calculated by dividing the total weight of CO_2 sequestered by the tree and the number of years the tree lives.

3. Results and Discussion

The results obtained from the identification of all trees, DBH measurements, and their relative positions to the central point, are shown in Table 1. With the relative location data, it was possible to depict the coverage and distribution of the crowns, as shown in Figure 6.

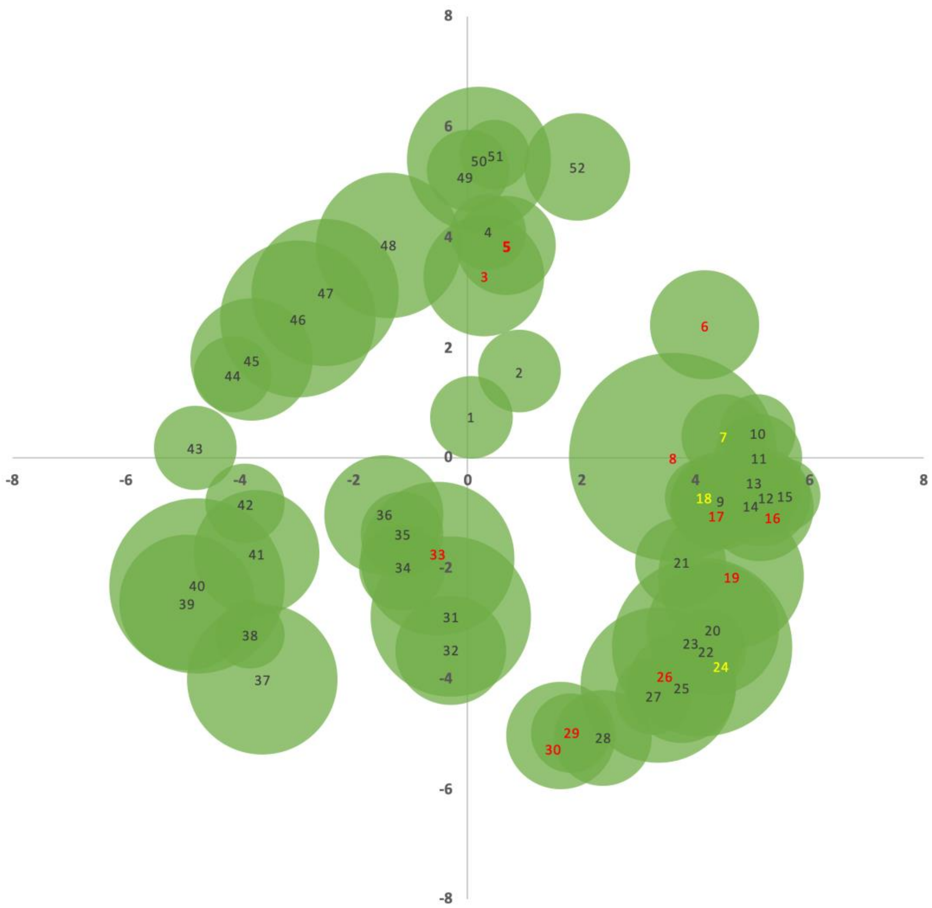

Figure 6. Projection of the *A. dealbata* crowns within the 15 m radius selected for the collection of samples. The samples identified in red correspond to those that were cut. Samples 7, 18, and 24, marked in yellow, correspond to the two trees of *A. unedo* and to the tree of *P. pinaster*, respectively.

Table 1. Data collected from the 52 samples that are inside the circumference with a radius of 15 m (*A.d.*—*A. dealbata*; *P.p.*—*P. pinaster*; *A.u.*—*A. unedo*; DBH—diameter at breast height).

Species	Sample no.	Distance (m)	Direction (°)	Direction (rad)	DBH_1 (cm)	DBH_2 (cm)	$DBH_{average}$ (cm)	DBH Class
A.d.	1	0.73	4	0.0698	4.7	4.8	4.75	5
A.d.	2	1.8	30	0.5236	5	4.6	4.8	5
A.d.	3	3.3	5	0.0873	10.6	9.9	10.25	15
A.d.	4	4.1	5	0.0873	4.4	3.7	4.05	5
A.d.	5	3.9	10	0.1745	7.1	6.7	6.9	10
A.d.	6	4.8	60	1.0472	9.7	7.2	8.45	10
A.u.	7	4.5	85	1.4835				
A.d.	8	3.6	90	1.5708	30.4	31	30.7	35
A.d.	9	4.5	100	1.7453	6.8	6.8	6.8	10
A.d.	10	5.1	85	1.4835	4.3	4.2	4.25	5
A.d.	11	5.1	90	1.5708	5	5.6	5.3	10
A.d.	12	5.2	97	1.693	4.2	4.1	4.15	5
A.d.	13	5.2	98	1.7104	6.5	6.8	6.65	10
A.d.	14	5.2	99	1.7279	3.5	3.5	3.5	5
A.d.	15	5.6	97	1.693	3.7	3.7	3.7	5
A.d.	16	5.2	100	1.7453	8.1	8	8.05	10
A.d.	17	4.4	101	1.7628	5.4	5.6	5.5	10
A.u.	18	4.2	100	1.7453				5
A.d.	19	5.1	115	2.0071	14.6	15.2	14.9	15
A.d.	20	5.3	126	2.1991	12.5	12.2	12.35	15
A.d.	21	4.2	117	2.042	5.9	5.7	5.8	10
A.d.	22	5.45	130	2.2689	4.6	4.5	4.55	5
A.d.	23	5.4	129	2.2515	3.4	3.6	3.5	5
P.p.	24	5.35	130	2.2689				
A.d.	25	5.6	138	2.4086	8.2	9	8.6	10
A.d.	26	5.3	141	2.4609	17.4	16.7	17.05	20
A.d.	27	5.4	143	2.4958	4.3	4.1	4.2	5
A.d.	28	5.6	155	2.7053	6.7	6.4	6.55	10
A.d.	29	5.3	160	2.7925	4.4	4.5	4.45	5
A.d.	30	5.3	162	2.8274	8.3	8.4	8.35	10
A.d.	31	2.9	186	3.2463	17.9	18.2	18.05	20
A.d.	32	3.5	185	3.2289	8.5	8.4	8.45	10
A.d.	33	1.9	196	3.4208	16.7	16.7	16.7	20
A.d.	34	2.3	210	3.6652	5.2	5.3	5.25	10
A.d.	35	1.8	220	3.8397	5.2	4.7	4.95	5
A.d.	36	1.8	235	4.1015	10.1	10	10.05	15
A.d.	37	5.4	222	3.8746	16.6	15.2	15.9	20
A.d.	38	5	230	4.0143	3.4	3.3	3.35	5
A.d.	39	5.6	242	4.2237	13	13	13	15
A.d.	40	5.3	244	4.2586	22.2	21.6	21.9	25
A.d.	41	4.1	245	4.2761	11.7	10.8	11.25	15
A.d.	42	4	258	4.5029	4.3	4.4	4.35	5
A.d.	43	4.8	272	4.7473	4.6	5.2	4.9	5
A.d.	44	4.4	290	5.0615	4.5	4	4.25	5
A.d.	45	4.2	295	5.1487	10.8	10.2	10.5	15
A.d.	46	3.9	310	5.4105	16.7	17.8	17.25	20
A.d.	47	3.9	320	5.5851	14.5	16.4	15.45	20
A.d.	48	4.1	340	5.9341	14.2	15.6	14.9	15
A.d.	49	5.2	0	0	4.6	4.8	4.7	5
A.d.	50	5.4	2	0.0349	14.3	15.4	14.85	15
A.d.	51	5.5	5	0.0873	3.6	3.2	3.4	5
A.d.	52	5.6	20	0.3491	7.4	8.7	8.05	10

The DBH was only measured for *A. dealbata* specimens; other identified species were ignored, namely, *P. pinaster*, with one specimen, and *A. unedo*, with two specimens. In other words, of the 52 trees analyzed, 49 correspond to *A. dealbata* trees. The DBH presented an average of 8.97 ± 1.66 cm, with a minimum of 3.35 cm in sample 38 and a maximum of 30.7 cm in sample 8.

Although the error introduced in measuring the crowns diameters and its shape, which was assumed as being circular, a very clear perception of the arrangement of sets of trees around a larger and older tree was obtained, which was probably responsible for the production of the seeds that gave rise to the others. The 49 specimens of *A. dealbata* in an area of 710 m^2 represent a density of 690 trees·ha^{-1}, in line with the normal density of non-planted forests in Portugal for species such as *E. globulus* or *P. pinaster*. Returning to the idea that acacias, especially *A. dealbata*, could be an option for bioenergy production, it may not be as profitable an option as it may appear at first glance. The physico-chemical properties of *A. dealbata* wood, as well as other invasive forest species, such as *A. melanoxylon*, *Robinia pseudoacacia* L., and *E. globulus*, with non-acceptable parameters for the pulp industry, are already well-known. There are several reporting the possibility of using this residual biomass for energy recovery, such as those presented by Sá et al. (2020), Nunes et al. (2020), or Álvarez-Álvarez et al. (2018) [32–34], especially if this recovery is associated to energy densification processes, such as torrefaction or pyrolysis. This seems to be an interesting perspective since even when there is no possibility to use the charcoals for energy purposes, those can be stored in the soil, sequestrating CO_2 [35–37]. This possibility, combined with the general idea that *A. dealbata* presents always a fast growth, being therefore a candidate species to be used both in the production of biomass or as a carbon sequestrating agent, in reality, is only valid if some conditions are confirmed, namely the access to sunlight.

The samples were then distributed by the categories established for the DBHs, and selected for cutting, measuring, and weighing, as presented in Table 2. This classification was intended to be as representative as possible of the 49 *A. dealbata* trees located in the defined area, but also due to accessibility to the tree and capacity to safely collect the samples. Class 5 totalized 19, corresponding to 38.7% of the *A. dealbata* population, while class 10 counted 28.6%, class 15 counted 18.4%, class 20 counted 10.2%, and classes 25 and 35 counted 0.02% each. The classes initially defined for 30 and 40 had no specimens.

Table 2. Distribution of samples by DBH classes.

DBH Class	Quantity of Trees	Identification of Selected Trees
Class 5	19	5, 17, 29
Class 10	14	3, 6, 16, 30
Class 15	9	19, 26, 33
Class 20	5	
Class 25	1	
Class 35	1	8

The results of determining the age, carbon content, and the quantity and annual productivity of the collected specimens are shown in Table 3.

Among the selected specimens, the youngest tree (sample no. 5) began its growth in 2013, being 5 years old at the date of the cut, which was carried out in October 2018. The oldest tree was sample no. 8, which started its growth in 1998, which was 20 years at the date of cutting in October 2018. The trees had an average age of 11.63 ± 2.32 years. The variance of the determined carbon content values was very small, 0.34, indicating that the deviations from the sample mean were very small. For this reason, the values are represented by their average, which is 48.85 ± 0.35%. The sample with the lowest value was sample no. 6, with 48.30%, and the sample with the highest value was sample no. 26, with 50.40%. The highest total weight was sample no. 8, at 594.8 kg, and the lowest was sample no. 29, with 4.1 kg. However, the value presented by this sample may be related to the tree being in poor condition, as was under a larger tree that shadowed it. The average total weight measured was 133.40 ± 103.66 kg. The average annual productivity was

9.42 ± 5.27 kg·year^{-1}, with the sample no. 8 presenting the highest value, at 30 kg·year^{-1}, while sample no. 29 presented the lowest value, with 1 kg·year^{-1}.

Table 3. Weighing the amount of aerial biomass and the annual productivity of the samples collected (w_w—trunk weight; w_{brl}—leaves and branches weight; w_a—total weight).

Sample no.	Growth Starting Year	Age (years)	C_{total} (%)	w_w (kg)	w_{brl} (kg)	w_a (kg)	Productivity (kg·year^{-1})
3	2008	10	49.30	52.5	2.1	54.6	5
5	2013	5	48.70	23.6	5.2	28.8	6
6	2004	14	48.30	29.7	3.8	33.5	2
8	1998	20	49.10	578.9	15.9	594.8	30
16	2008	10	48.70	45	2.8	47.8	5
17	2009	9	48.40	14.2	4.3	18.5	2
19	2006	12	48.90	145.8	21	166.8	14
26	2004	14	50.40	223.6	25.5	249.1	18
29	2012	6	48.70	3.6	0.5	4.1	1
30	2009	9	48.80	43.5	2	45.5	5
33	2004	14	48.50	205	18.9	223.9	16

The possibility of using fast-growing species, such as those belonging to the genus *Acacia*, as sources of biomass for energy have been raised by several studies. Gasol et al. (2010) compared acacia species with other short-rotation common Southern European countries crops, such as Italy, from a techno-economic perspective of production viability [38]; Lenis et al. (2013) also studied the use of short-rotation crops for bioenergy with acacias and eucalyptus in Colombia, but focused more on the perspective of the physico-chemical properties of derived fuels and their potential for energy recovery [39]. This dispersion of studies and research work, examples of which can be found in Brazil [40–42], South Africa [43,44], China [45,46], in addition to those already widespread in Europe or the United States of America [47,48], highlights the need for these regions over the past few years to control the dispersion of species belonging to a genus originating mainly from Australia, which has spread to practically all regions of the world, causing serious problems to the local biodiversity, as they enter into direct competition with indigenous species [49].

The high productivity of these species has often been a factor driving their introduction into new habitats, rarely with a prior study of the potential impacts of this introduction. The effects on native species, which start competing for access to nutrients and for area with highly aggressive species, which have developed in very harsh environments with scarcities of water and nutrients, are one example of the research that should be conducted [50]. This type of species, when in the presence of the conditions for its development, presents a fast growth rate, guaranteeing access to nutrients and, especially, to sunlight, without which the growth stall or is reduced to a minimum [4]. It is this heliophilous characteristic that allows them to grow almost exponentially, but it also limits their development from the moment that this access to light is conditioned [51].

In Portugal, several studies have already been carried out on the development of various species of acacias, such as the work presented by Rodríguez-Echeverría et al. (2009) on belowground mutualists and the invasive ability of *Acacia longifolia* in coastal dunes [52], or the work presented by Santos et al. (2013). Variation in some wood macroscopic properties along the stem of *Acacia melanoxylon* R. Br. adult trees were noted [53]. With *Acacia dealbata* being the species with the greatest dissemination in Portugal, Martins et al. (2016) presented forms of invasive alien mapping of *Acacia dealbata* Link using ASTER multispectral imagery to quickly identify the areas seriously affected by this species [54]. This species has attracted the most attention mainly due to its high rate of [55], but also because of the difficulty that often exists in identifying the problem and in making decisions about the measures to be taken to control and combat it. A recent study by Vaz et al. (2020) assessed stakeholders' perceptions in Northern Portugal about these non-native acacias and their invasion processes, social–ecological impacts, and management, and verified the existence of a great lack of knowledge (and experience) regarding the recognition and identification of non-native trees, as well as that on their introduction and invasion history, drivers of dispersion, costs and benefits, and effective management [56].

The results obtained for determining the weight of carbon stored by each of the trees in the sample and the annual rate of carbon sequestration are shown in Table 4.

Table 4. Carbon sequestration per tree and annual rate of carbon sequestration (ARCS, annual rate of carbon sequestration).

Sample no.	C_{total} (%)	Moisture on Cut (%)	w_{total} (kg)	dw (kg)	w_{carbon} (kg)	w_{CO2} (kg)	ARCS (kg·year^{-1})
3	49.30	48.30	54.60	28.23	13.92	51.07	5.11
5	48.70	48.65	28.80	14.79	7.20	26.43	5.29
6	48.30	42.10	33.50	19.40	9.37	34.38	2.46
8	49.10	38.30	594.80	366.99	180.19	661.31	33.07
16	48.70	44.12	47.80	26.71	13.01	47.74	4.77
17	48.40	39.74	18.50	11.15	5.40	19.80	2.20
19	48.90	40.53	166.80	99.20	48.51	178.02	14.84
26	50.40	38.56	249.10	153.05	77.14	283.09	20.22
29	48.70	36.18	4.10	2.62	1.27	4.68	0.78
30	48.80	45.71	45.50	24.70	12.05	44.24	4.92
33	48.50	42.78	223.90	128.12	62.14	228.04	16.29

w_{carbon} had an average value of 39.11 ± 31.54 kg. Sample no. 8 had the highest value, at 180.19 kg, and sample no. 29 had the lowest value, 1.27 kg. w_{CO2} has an average value of 143.53 ± 115.76 kg. Sample no. 8 had the highest value, at 661.31 kg, and sample no. 29 had the lowest value, 4.68 kg. The ARCS showed an average value of 9.99 ± 5.91 kg·year^{-1}. Sample no. 8 presented the highest value, with 33.07 kg·year^{-1}, and sample no. 29 presented the lowest value, 0.78 kg·year^{-1}. In reality, this supposed biomass production capacity attributed to *A. dealbata* only happens in specimens with direct access to sunlight, and this productivity is compromised as soon as one specimen overlaps another, preventing access to direct light, inhibiting its growth and development in the medium and long terms. Figure 7 presents a projection of the carbon sequestration capacity for a period of 25 years based on the values of the annual carbon sequestration rate for each of the samples from the Casal de Rei stand. The calculations with the *A. dealbata* stand under study in the present work verified that there was no consistency in the results regarding CO_2 capture and sequestration capacity, which are directly related to its growth and biomass production. In the analyzed samples, in some cases, the amount of biomass produced appeared to be high. However, in other samples analyzed, this biomass production was very low. This difference in productivity is directly related to its position in the stand, with the distribution shown in Figure 6.

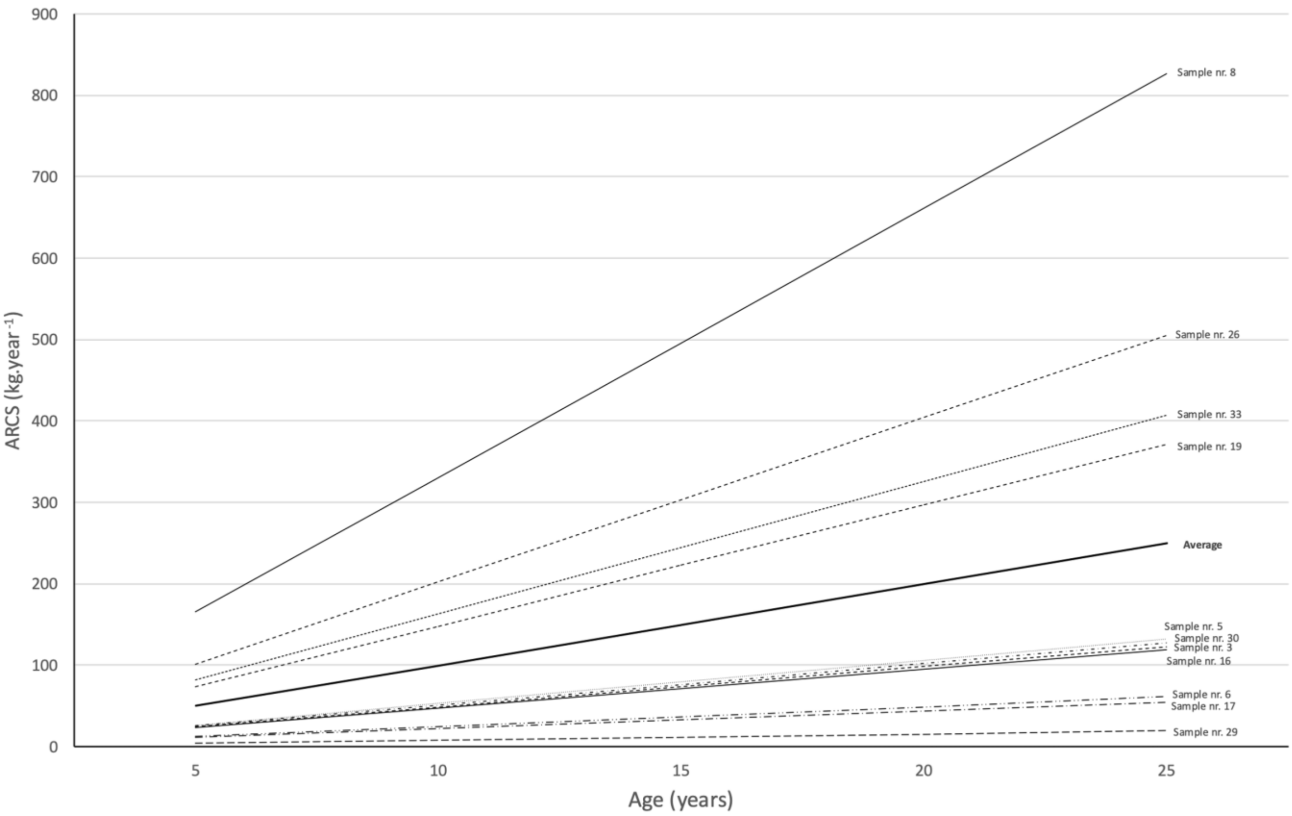

Figure 7. Simulation of carbon sequestration capacity in the medium and long term for *A. dealbata*.

As can be seen, the four samples (no. 8, 19, 26, and 33) that showed a higher capacity for sequestration, proven by their greater total weight, were those that presented a dominant position in the settlement space and a greater total height. The remaining samples, as can be seen in Figure 6, were located in the vicinity of these or other dominant samples and were therefore considered to be dominated by larger ones. In these cases, the development remained very slow and much lower than that observed for the dominant samples. Thus, was inferred that the use of species such as *A. dealbata* as a short-rotation energy crop would have to obey spacing criteria that would allow trees to access light, or risk jeopardizing their development in the medium and long terms, although the use of tight calipers in the early developmental stages is common for promoting faster initial growth.

Because this accelerated initial growth may imply a reduction in the quality of the physical and chemical properties of this wood, its use as a fuel in bioenergetic applications, such as the production of wood and wood pellets, does not seem to appear to be feasible from the perspective of using it in short rotation coppice models. However, the energetic valorization of this and other similar species seems to be a possibility to enhance its control and eradication, since, by creating value chains to enable the use to these residual biomasses, it allows the reduction in associated costs and enables the creation of sustainability in the control and eradication processes. The prospect of carbon capture and sequestration through the thermochemical conversion of these residual biomasses provides a new method for mitigating climate change, as previously mentioned, since the carbon captured and sequestered by plants during their lives is stored, for example, in soils or landfills prepared for this purpose.

Nunes et al. (2020) determined the productivity of 17.5 t·year^{-1}, corresponding to a growth after cutting for four years, with all the biomass cut and weighed in two hectares, totaling 140 tons. However, the quality of the biomass presented, all of low diameter, was characterized in terms of its physicochemical properties and used in the production of wood pellets, but did not meet the requirements of quality control standards such as

ENPlus® [33]. However, as also described by Rodrigues et al. (2018), the properties of several short rotation coppices and some residual biomasses were characterized. The combustibility of some of these biomasses, namely that of *A. dealbata* but also of others, due to the high levels of chlorine and alkali metals, affect the performance of energy recovery equipment when used without any pre-treatment, but significantly improve when undergoing a thermochemical conversion process, in this case, torrefaction [57].

A. dealbata highly dense forests will not produce biomass with sufficient quality for direct energy recovery or to other bio-based uses, mainly due to the heterogeneity of the specimens, although in the first years, are capable of producing a large amount of biomass caused by the intense competition between the shoots. However, this initial fast growth cease when the dominant specimens appear, which inhibiting all others surrounding. Thus, the potential of using this biomass for charcoal production seems to be the most interesting, since it envisages two uses: energy recovery through charcoal, and carbon sequestration. This use can provide an ecosystem service framework for the process of controlling invasive species, which goes beyond preserving biodiversity and reducing the risk of rural fires, as this new aspect can be seen as a mitigating measure for climate change. Other approaches, with different bio-based uses should be considered as well, being a research field with high potential for new developments, e.g., the green chemicals industry.

4. Conclusions

Biological invasions are problems that require an integrated approach to their solution, mainly because the complete eradication of the invasive species is not possible, particularly because the species become naturalized and adapt their biological cycles to the invaded ecosystems. This adaptation to local edaphoclimatic conditions the control and eradication of species, in most cases, challenging. The creation of value chains that can minimize the costs associated with operations to control and eradicate invasive species seems to be a method that can contribute to reduce costs associated with these management operations, allowing them to become more sustainable. The possibility of incorporating these biomasses into the supply chains of energy recovery processes is a solution that is already in place in Portugal but can still be further enhanced. However, other possibilities, such as the production of materials with high carbon content, such as charcoal for carbon sequestration, is a possibility that must also be considered since this option can be included in the measures to mitigate climate change. The possibility of using *A. dealbata* as an energy crop or for the creation of natural carbon sinks with the maintenance of acacia forests does not seem to be an option that justifies the risk of uncontrolled proliferation of the species. Its growing capacity is dependent on factors such as access to sunlight, so the development of dense acacia forests does not present a large ability to capture and sequester carbon in the medium and long terms. Otherwise, these dense forests may potentiate other risks, such as the occurrence of rural fires, due to the increased accumulation of biomass, but mainly due to the loss of biodiversity in this type of stands.

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CHAPTER 6 – DISCUSSION AND CONCLUSIONS

Chapter Index

6.1. Climate Change and the Spread of Invasive Species

As a global phenomenon, climate change affects all system components, especially regarding biological development. Living beings evolve and adapt to a particular set of ecological factors, including the physicochemical characteristics of the soil and the atmosphere. These specific characteristics also become conditioning factors, especially with respect to plants, leading to their evolution and adaptation to the soil and climate conditions of a given location. This conditionality of plants is related to their immobility as adults, since it is expected that during their life cycle they acquire mobility only in the seed dispersal phase. Moreover, even this mobility is dependent on external factors, such as the wind, which can transport the seeds over great distances; the water, which transports them to a new location where they can germinate; or even animals, which ingest the seeds and then egest them far away from their origin. However, invasive species' dispersion processes are rarely associated with natural dispersion processes, as the time taken for these to produce significant effects in the areas of occupation is extremely long. This dispersion by natural means occurs gradually, while the soil and climate conditions remain constant (apparently) with the place of origin of the species (which is said to be indigenous to that place). However, as soon as edaphoclimatic conditions change—for example, due to variations in soil composition, in water availability, or in air temperature—the expansive progress of the species can be immediately blocked. On the other hand, the arrival of seeds at a place that does not present the ideal conditions for their development does not mean that the species is doomed to failure in that place, being able in many cases to survive, albeit without the robustness that they would present if the conditions were more favorable. In this case, the species (now allochthonous) begins a long naturalization process; that is, the species will evolve to adapt to the new edaphoclimatic conditions of its new habitat.

When a species progresses territorially and reaches a place where the soil and climate conditions present more favorable characteristics than those in the original location, a faster development of the species can occur. In this case, this allochthonous species will enter into direct competition with the autochthonous species that have developed and adapted to the existing conditions. In this case, allochthonous species have evolved and adapted to more severe conditions, so their physiological systems react positively to this new abundance of available resources, with a development that can be figuratively considered exponential. This situation creates a scenario of direct competition between native and alien species, where the latter have advantages as they have evolved under more adverse conditions. In this way, they conquer more territory in the new habitat and are considered to acquire an invasive behavior.

Nevertheless, the natural processes of seed dispersal over time do not seem to have had a negative impact on the progression of species across the planet since, as mentioned, this was a slow process of progressive spreading over millions of years, with the adaptation of ecosystems in all of their aspects. Currently, processes can be (and are) accelerated due to human intervention. Since ancient times, human migrations have been accompanied by their belongings, i.e., their biological assets, which primitive humans learned to use. Examples of this are the many species of domestic animals, such as dogs, cats, horses, pigs, cows, sheep, goats, and chickens, among many others, as well as numerous plant species, such as cereals, fruit trees, and vegetables. More recently, with the economic globalization that took place after the historical period of the Discoveries (i.e., the 15^{th} century onwards), a particular curiosity for the unknown also led to the collection and transport of species from different sources—initially to Europe, but then also to other parts of the colonial empires. In many cases, species with the capacity to provide raw materials were transferred. However, with the increase in the interest in scientific knowledge that took place after the Renaissance and the development of the concept of the aesthetics of urban spaces with the creation of gardens, many species were planted, spread, and displayed as a sign of a particular social status, demonstrating access to exotic products from distant territories. This situation, repeated in Portugal, was also common to other European colonial empires, and later to the United States of America.

This rapid dispersion of species did not present any problem, as the specimens planted in urban areas were permanently controlled, and their numbers did not allow an impactful dispersion in the surrounding habitats. However, the progressive abandonment of these spaces, probably due to the progressive lack of interest caused by the monotony of the theme, led these species to start a slow expansion out of the controlled spaces, reaching natural spaces, where they slowly began to compete with native species, although initially the impact on ecosystems was not significant. The factor that may have tipped the scales toward the development of alien species must have been the beginning of the effects of climate change, associated with the continuity of an increasingly intense form of human intervention in the natural environment.

Climate change corresponds to a set of changes correlated with one another that affect systems at different scales. For example, the observed variations in the average temperature of the surface air layer of the planet lead to changes in the formation and circulation regime of the winds that, in turn, lead to changes in the air moisture distribution regime. These processes can occur either on a large scale, altering the climate of the planet, or on a small scale, causing regional alterations, such as localized droughts. An example such as this can contribute to profound changes in the soil and climate conditions of a region, reducing the ability of native species to thrive and causing their migration to more favorable positions, as shown in Figure 6.1.

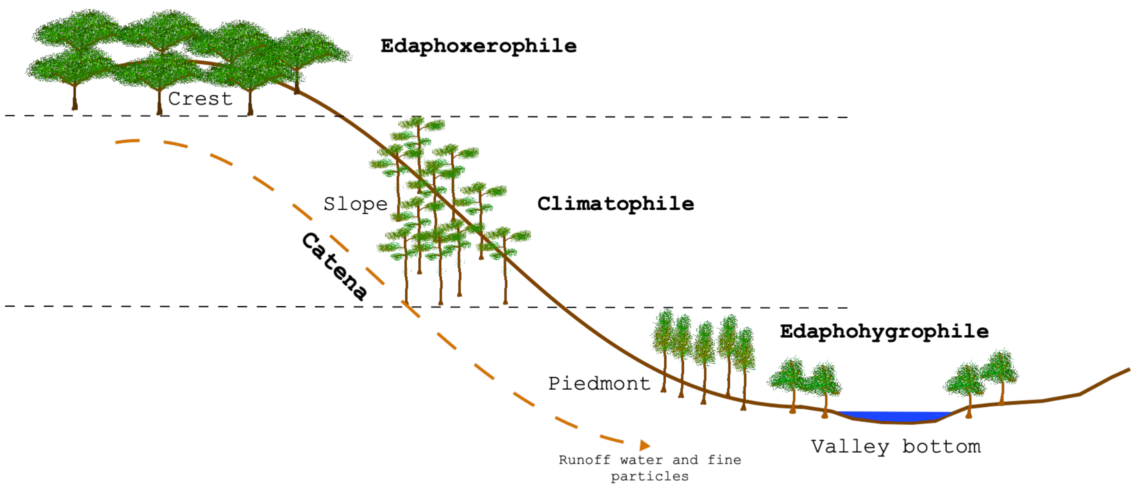

Figure 6.1. Schematic representation of the topographic geosigmeta (adapted from (Loidi, 2021)).

Figure 6.1 shows the crest-slope-piedmont-valley bottom sequence, which is universally applicable. At the top of the orography is the edaphoxerophile sigmetum, which is the most xerophytic. In the slope region and part of the piedmont is the sigmeta climatophile. In the bottom valley is the sigmetum edaphohigrophyle, which corresponds to the most humid zone. Geosigmeta are organized by the gradients of soil moisture and depth, created by the slope factor, which causes water runoff and particles in the soil. Erosion is prevalent in the crest and sedimentation in the bottom valley, where the finest particles, nutrients, and moisture accumulate. With the variation in edaphoclimatic conditions, successive migration can occur along the slope, with the species advancing towards the bottom valley, where they cause pressure on the species of the sigmetum edaphohygrophile.

On the other hand, the alien species already in place, as they evolved in more adverse environments, continue to thrive, only this time with clear superiority and advantage over the native species. With this new competitive advantage guaranteed by the effects of climate change, aided and enhanced by human action, there is an acceleration of expansive processes, with the occupation of territories previously belonging to native species. In this case, the alien species that initially only occupied the marginal territories of the new habitats, usually not claimed by the native species due to inadaptation, literally start to invade other spaces, increasing their area of occupation of the habitat until they dominate it. This dominance is achieved by supplanting native species in an occupied area, significantly impacting the ecosystem. For example, a species may have a specific set of species associated with it that depend on it for food, but when they see this species replaced by another, they are forced to leave the habitat, causing a series of chain impacts on all of the species that interact with or are interdependent on one another.

Climate change can interfere with ecosystems in other ways, causing even more negative impacts on biodiversity and the survival of established habitats. The disturbance of hydrological cycles currently observed, with the concentration of precipitation periods at certain times of the year, with this precipitation occurring intensely, and alternating with subsequent periods of increased temperatures and insulation, causes changes in the growth cycles of the species. These variations lead to explosive moments of plant growth, which can/should be analyzed from the perspective of increasing the available fuel load, with the increase in dry periods caused by the concentration (and reduction) of precipitation in some areas of the planet, contributing significantly to the increased risk of rural fires.

On a global scale, there has been an increase in the number of occurrences, with such fires appearing not only in the usual regions, but now appearing in latitudes where they were only part of the landscape under very particular and abnormal situations and conditions. Examples of this are the cases seen in regions such as Siberia, Scandinavia, or Alaska. On the other hand, in Mediterranean-type climate regions, there has been an increased risk and number of occurrences, as these regions are considered hotspots for climate change. In other words, they are identified as being in the regions where the effects of climatic situations are felt with greater intensity. This situation further enhances the dispersion process of certain types of invasive heliophyle and pyrophyte plants, with these two intrinsic characteristics being competitive advantages. In this way, these species benefit from the occurrence of fire, as the flames eliminate the vegetation cover, allowing the seeds to germinate without competition for access to direct sunlight. In contrast, the heat generated by the flames serves as an activator of seed germination because the seeds are resistant to high temperatures and are not destroyed. In this scenario, fire acts as a facilitator by eliminating the vegetation cover but also contributes to eliminating the seed banks of other species not resistant to fire.

The continued action of fire leads to a process of artificial selection of species in a changing ecosystem, where the selection of species does not occur through processes of adaptive evolution to the conditions (which takes a long time to occur naturally), but instead occurs artificially, via a process that eliminates the species that cannot adapt to these new conditions. In the case of the Mediterranean landscape, fire has always been a part of biological cycles as an ecological agent. However, there is a greater recurrence of fire episodes in the current climate change scenario and due to the abandonment of rural areas. As the germination capacity of invasive species (such as acacias) is very high, and they can present an almost exponential growth rate in their first years of life, the recovery of the fuel load of a burned area is very fast. With the reduction in precipitation, the increase in average air temperatures, and the lack of management of the rural environment, the conditions for an increase in the risk of fires are met. This is how fire shapes the landscape in favor of invasive species, because when it occurs more frequently, it promotes the development of pyrophyte invasive species, to the detriment of other species, which are slower to recover. With this behavior, the Mediterranean landscape is progressively giving way to a new type of ecosystem, with the dispersion of invasive heliophyle and pyrophyte species.

In Portugal, the situation takes on concerning contours, with the increased risk of rural fires and the growing expansion of several invasive forest-type species, such as *A. dealbata*, *Robinia pseudoacacia*, *A. melanoxylon*, *Ailanthus altissima*, or *Gleditsia triacanthos*, which show different behaviors depending on the region in which they can be found. However, perhaps the species that raises the most significant concern is *A. dealbata*. This species contributes significantly to the area occupied by invasive species and has been frequently (and repeatedly) identified as a beneficiary species in post-fire recovery. The current scenario, where there is a strong influence of climate change and increasing human intervention, is conditioning the evolution of forests in Portugal—firstly, from an environmental perspective, and secondly, constraining the biological relationships between the species that make up the habitat. Climate change—direct or indirect—and human action are undoubtedly the leading causes of the destruction of ecosystems and the loss of biodiversity. Thus, they contribute to the competitive favoring of invasive over native species. However, these negative impacts are not only felt from an environmental perspective and in the loss of biodiversity, but are also felt deeply in the other ecosystem services that forests provide, which also acquire important contours of a socioeconomic nature.

The role of forests in the Portuguese economy is crucial, with some of the leading national economic groups supporting their activity via the forests, associated with the exploitation of the three dominant tree species. In this case, maritime pine, eucalyptus, and cork oak represent approximately 2/3 of the national forest area and are responsible for supplying fundamental raw materials for industries such as pulp and paper, wood agglomerates, wood pellets, furniture, and cork, among others. The increase in the area occupied by invasive species, such as *A. dealbata*, provokes competition with production species, causing drops in productivity, which will undoubtedly have negative impacts from an environmental, economic, and social point of view. The increased risk of fire—boosted by climate change, but essentially due to the lack of management—also contributes significantly to negative impacts on the productivity of forest systems. The combination of these factors also contributes to the weakening of trees, making them more susceptible to pests and diseases and, thus, less able to compete with the pressure caused by invasive species.

6.2. The Control of Invasive Species and the Creation of Value Chains

The problem associated with the dispersion of invasive species has been studied using the most diverse approaches and perspectives. The main objective of the control and eradication actions carried out is to contain the infestation and prevent its proliferation to new areas, as well as to find ways to reverse the invasion by eliminating all of the specimens. However, despite the efforts and means used in these actions, the reality of the results has not been favorable for control—much less eradication. There are several factors that tip the balance towards the invaders, which continue to proliferate. On the one hand, the robustness that these species present allows them to resist successfully even when conditions are adverse, often even managing to obtain competitive advantages over native species, which are less prepared for rapid adaptation to the new conditions in a climate change scenario. The ability to quickly germinate in post-fire scenarios from seed banks, which can wait for an opportunity for years, also presents a competitive advantage, allowing these species to conquer space, establishing themselves without competition. On the other hand, control and eradication actions entail very high costs, meaning that they are not carried out with sufficient (human and material) means or with the frequency necessary for the definitive success of the operations. In this way, with natural factors forcing the success of the definitive establishment of invasive species and with aspects dependent on human action being hampered by financial and practical shortages, control and eradication actions urgently need to be planned under the terms of new approaches—for example, by including the material (biomass) in the existing recovery chains of the different forest operations or by creating new ones when the situation justifies it.

Currently, the valorization chains already implemented in Portuguese forests are very focused on the use of maritime pine and eucalyptus biomass, with the former contributing to the wood pellet industry, the biomass pellet industry, the furniture industry, the production of pallets, and the pulp industry (used in the production of kraft paper) as preferred destinations. Eucalyptus biomass is essentially intended to be used in the production of paper pulp (mainly in the form of bleached pulp). Residual biomass resulting from the management operations of these production forests is usually valued as biomass for energy or is abandoned or burned in piles without any use. The possibility of including the biomass resulting from the control and eradication operations in some of these recovery chains allows a material with no form of use to become practical and acquire value. In other words, the materials resulting from actions that previously only represented a cost (although the advantages were evident from the environmental point of view) may now also be able to contribute to the cost-benefit balance through financial means, as exemplified in Figure 6.2.

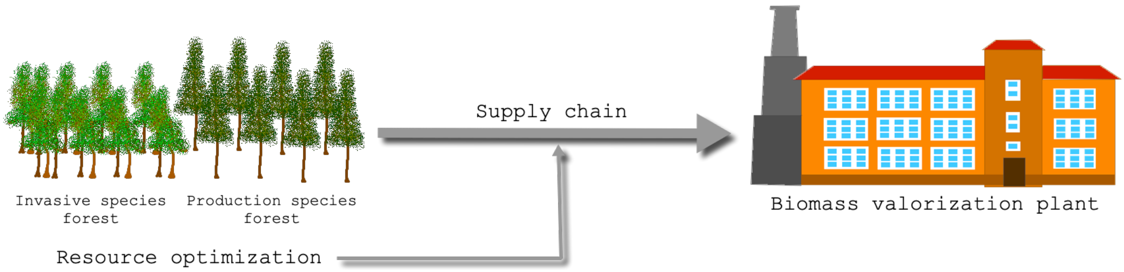

Figure 6.2. Material flow and value creation process in inclusive and adaptive forest management models.

Figure 6.2 represents a generic example of an inclusive forest management model. It optimizes the resources already available for the control of invasive species, adapting to the supply chain already in use, for the management and valorization of biomass resulting from control and eradication actions, together with those resulting from production forest management operations. In this way, there are several advantages from a financial point of view since, firstly, the biomass resulting from these actions—generally classified as residual—can be included in batches classified as raw materials (for example, for the production of biomass pellets), being therefore valued in another way (with value gains). Secondly, by being processed in a planned and organized manner with the everyday production forest management actions, the costs associated with control and eradication actions are diluted in the total operational costs, where economies of scale have clear advantages through optimization of the available resources. Thirdly, the continuous control of invasive species contributes to their competition with production species in their favor, thus avoiding drops in productivity caused by direct competition and reducing the risk of fires occurring in these forest species by permanently reducing the fuel load. Fourth, and finally, the valorization of these biomasses (previously classified as residual), due to the financial contribution they create, makes it possible to continue these actions sustainably (in all aspects) for long periods until the definitive success of the actions. This success is achieved by exerting constant pressure on invasive species, which, as they do not have time to recover effectively, are weakened, leaving the possibility of recovery of stands very dependent on seed banks, which are no longer being supplied with new seeds. This (long) process allows the production species to reoccupy the space previously occupied by the invasive species and, with the advancement of the development of the new trees, the shading makes it difficult—or even impossible—for the germination of new specimens of the invasive species to take place.

However, although the application of a model such as the one described above seems easy and evident with respect to supply chains from production forests, its applicability in conservation forests can raise great difficulties, as the inexistence of any implemented supply chain or the possibility of recovery for waste materials can create constraints on the feasibility of the model. These forests often include protected species, with their valorization (at least of the biomass) being restricted. Moreover, they are constituted by species in which the form of greater valorization is associated, for example, with the fruits and not with the biomass, which can make it challenging to optimize the available resources, as this forces stakeholders to move other means to control and eradicate invasive species. In these cases, control and eradication actions are likely encouraged from a preventive service perspective, with the aim of, for example, avoiding drops in productivity caused by competition between species, or reducing the risk of fire. In these situations, the cost of control and eradication actions seems to be assumed as a necessary cost from the perspective that the (ecosystem) service provided by the conservation forest justifies the financial effort, even when it is difficult to quantify the value of these conservation ecosystem services (which may be tangible or intangible). From this perspective, creating a value chain cannot be understood in the same way as presented above. In this case, the direct valorization of the material resulting from the actions of control and eradication of invasive species is not assumed; rather, the forest system is valorized through the elimination of invasive species. Figure 6.3 presents a schematic representation of the value creation model for the scenario described above.

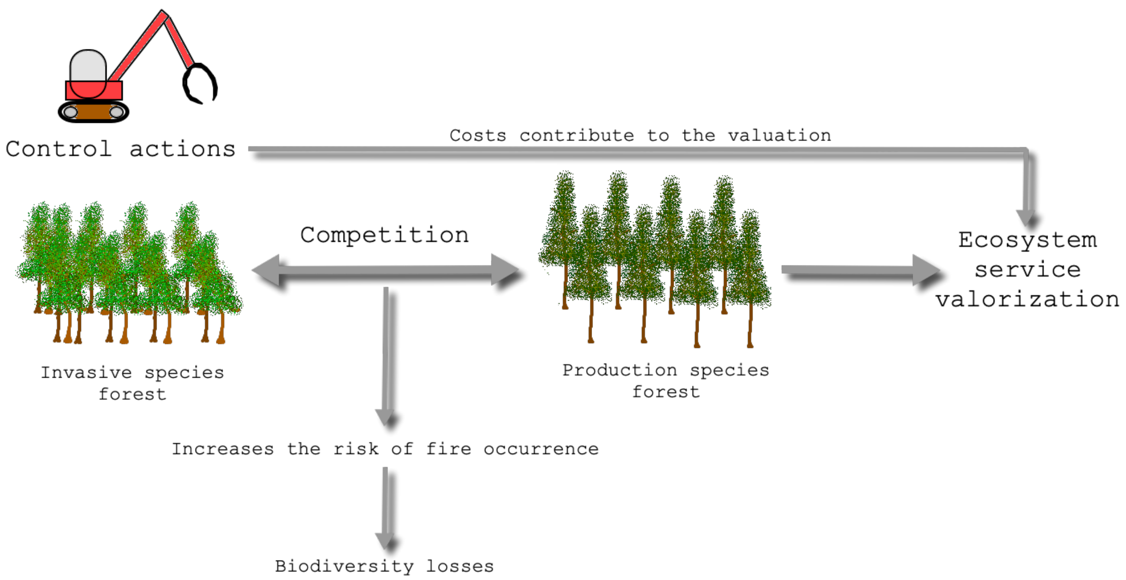

Figure 6.3. Model that justifies the cost for greater appreciation of ecosystem services.

However, the creation of a model for an indirect value chain is still challenging to understand, as the difficulty in quantifying it from the perspective of attributing a value to intangible services—such as landscape, biodiversity, or carbon capture and sequestration—can contribute to the impact and relevance they may have in the indirect creation of value for the entire forest system when deciding on the actions to be implemented. In these situations, resorting to the optimization of resources in a sharing regime, as shown in Figure 6.4, seems to be a solution with high potential. However, although more or less prominent, this solution may face some of the major problems facing forest management in Portugal—namely, the excessive partitioning of the territory (which forces the comparison of the interests of the different owners) and the intricate mosaic caused by the permanent discontinuities in the types of occupation and land use that occur mainly in the Norte and Centro Regions of Portugal.

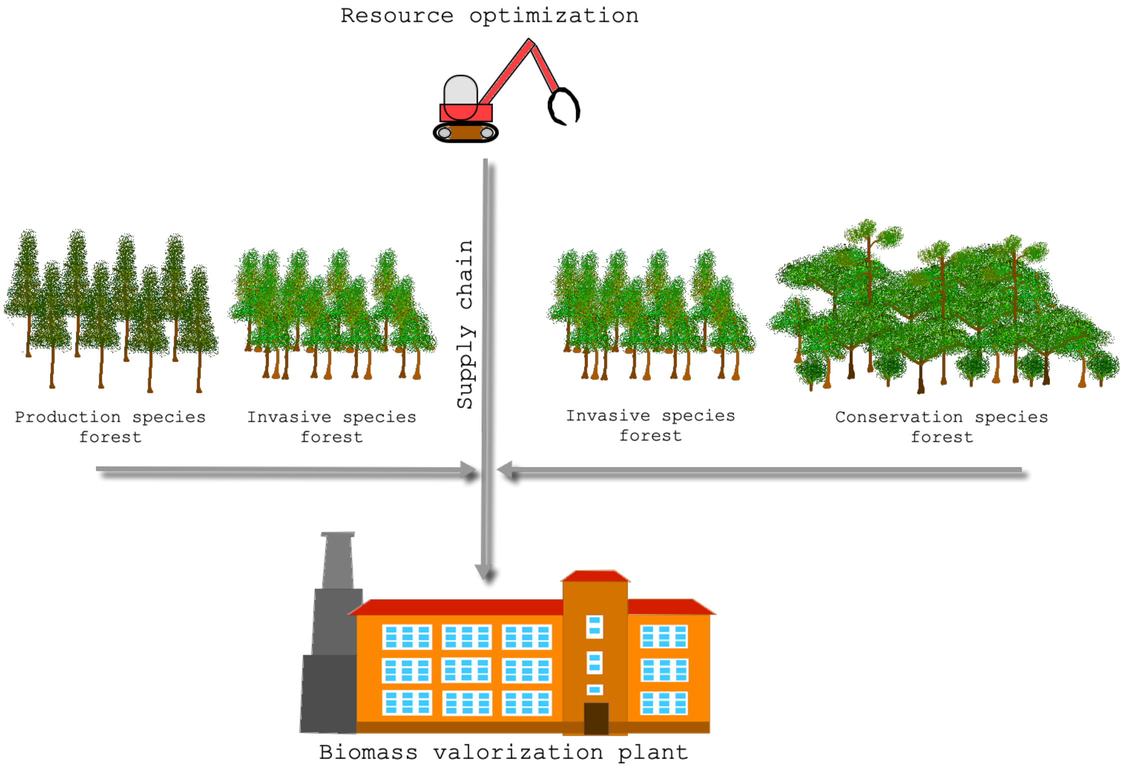

Figure 6.4. Resource optimization model in a sharing regime.

This resource optimization model implies coordination that can present a complete image at a regional scale in order to be able to organize the available resources so that they can optimize, for example, downtime in a given location, taking advantage of this break to be able to perform another task in a nearby location without causing interruptions or delays in any work front. In addition to the knowledge of the available means (which implies a close relationship with service providers—usually private), the organization must have some ascendancy over the owners and other agents involved in the process, as only in this way is it possible to conciliate and coordinate the different interests of each of the parties. In other words, this is a value chain creation model that implies the aggregation of interests to achieve an appreciation of the resource as a whole, in an integrative perspective of the system as a whole, and with the evaluation of all of the recoverable components (Figure 6.4).

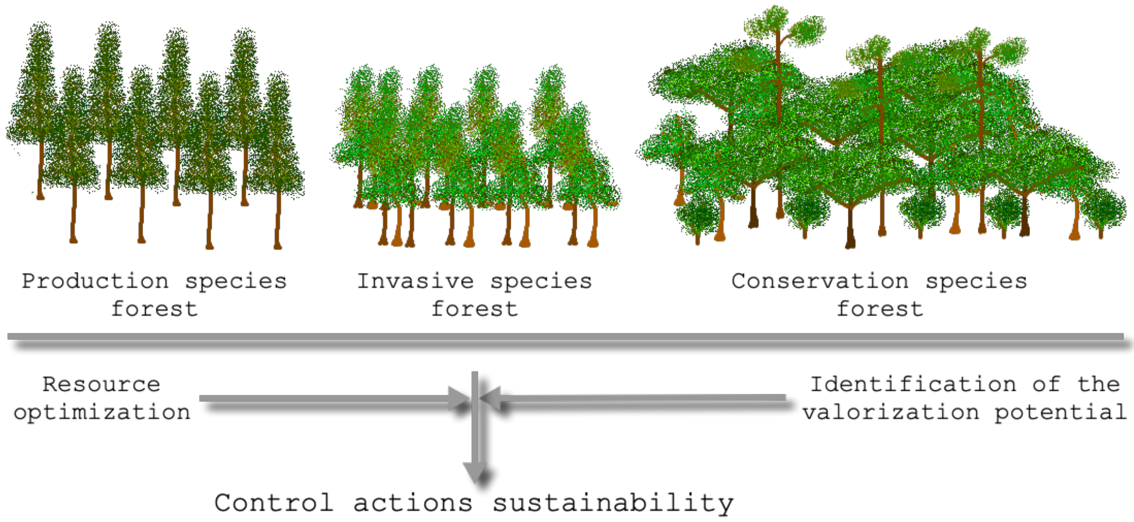

Figure 6.4. Integration model of the different types of forest, with the objective of creating value chains to enhance the sustainability of invasive species control actions.

Whichever model is used, the most obvious way of valuing materials resulting from invasive species control actions focuses on the energy recovery of these materials. Although its inclusion in the group of residual biomass makes its value fall compared to the value of the biomass included in the group of round wood, the possibility of directing it to energy recovery (directly or indirectly) allows large volumes of material to have a destination. From the point of view of quantities, if residual biomasses are considered to present lower heating values of 8.77 $MJ \cdot kg^{-1}$ and 10.47 $MJ \cdot kg^{-1}$ for undifferentiated materials composed of trunks, branches, and pecks with 50% and 30% humidity, respectively (for example, from *A. dealbata*), the quantities needed to supply biomass thermal power plants are shown in Table 6.1.

Table 6.1. Approximate amounts of residual biomass (consisting of undifferentiated materials composed of trunks, branches, and pecking, with 30% and 50% humidity), assuming an operational availability of 85%.

Installed Power (MW)	**30% Moisture Biomass Quantity ($t \cdot year^{-1}$)**	**50% Moisture Biomass Quantity ($t \cdot year^{-1}$)**
2	5000	6000
5	12.500	15.500
10	25.500	30.500
50	128.000	152.000

Despite valuing the biomass resulting from the control actions less, the direct energy recovery in biomass thermal power plants is much less demanding in terms of the quality requirements of the materials, accepting all parts of the trees (branches, trunks, pecking, roots, etc.). On the other hand, valorization through incorporation into the supply chains of the wood pellet industry—which values materials with significantly higher values—is much more demanding in terms of quality, rejecting parts of the trees that are known to interfere with the quality of the final product, especially when it is the object of some certification, as is the case of certification by the ENplus® standard. Even the most valued fraction (i.e., the trunk) of species such as *A. dealbata* can only be incorporated in the process gradually, as it contains some elements that negatively vary the limits presented in the standard. For example, the chlorine content of *A. dealbata* is approximately 0.08%, and the limit allowed by the standard is 0.04%. However, mixing it with maritime pine, which has a content of approximately 0.02%, is possible in proportions that match between 60% and 75% maritime pine biomass, with 25% to 40% from *A. dealbata*. However, additional attention to other parameters is necessary. *A. dealbata* also has extremely high nitrogen values, which in thermal conversion processes can release NO_x, and significant contents of alkali metals, which alter the potential of corrosivity in thermal conversion equipment by lowering the fusibility temperature of the ashes. In any case, the energy recovery of the biomass resulting from the control actions of species such as *A. dealbata* can be used to create pressure on the stands, and in this way, by creating value, can contribute to the sustainability of control actions through the financial contribution to the cost-benefit balance.

6.3. Evolution of Forest Management Models from the Perspective of a Climate Change Scenario

The impact of climate change on forest systems is very significant at several levels, as the effects are effectively felt in the variability of environmental parameters, which is reflected in the development of forest stands and the relationships between the species that constitute them. Ecosystems are complex systems consisting of different habitats related to one another at various scales and levels, where intra- and interspecies relationships, together with environmental factors, establish a dynamic balance in permanent oscillation and rebalancing. This rebalancing is essential for maintaining mass and energy balances and, thus, the sustainability of the system. However, if an internal analysis of the relationships and balances that occur at the scale of a system is carried out, it is possible to assume that it behaves as if it were closed, with no exchanges with the outside (in the form of flows of mass and energy) taking place; in reality, natural systems are not closed and relate to neighboring systems.

These intersystem relationships also depend on balancing mass and energy flows. When these equilibria are broken, one of the systems acquires some ascendancy over the other, being able to consume it (or absorb it). When a set of external factors starts to influence a system, it can be considered that, depending on the strength of these externalities, the system can evolve to a new state of stabilization, where its constituent elements can respond positively to external stimuli. On the other hand, when a system's constituent elements are incapable of responding to external stimuli, the system weakens, and the balance towards which it evolves becomes favorable to the allochthonous elements.

The competition between invasive and indigenous species is an example of such a situation, with climate change acting as a set of externalities that tip the balance towards invasive species, to the detriment of indigenous species. Based on these scenarios, the level of resilience of a system can be defined as the ability of that system to recover equilibrium (understood as being the zero level or the starting point of an evaluation) up to the conditions in which it found itself the moment immediately preceding the point when it began to feel the effects of factors external to the system.

In the current climate change scenario, there is a tendency towards the dispersion of invasive species that compete directly with the established species. At the same time, there is an increase in the risk of rural fires, mainly due to the combination of the increase in fuel load (caused by several factors, including the dispersion of woody invasive species and the inexistence of management) with the most adverse climatic conditions (with less precipitation and higher temperatures). If these factors are considered externalities that negatively impact forest systems, the level of resilience of that system is defined, as mentioned, by its ability to recover.

The problem observed is that forest systems (made up of production forests or conservation forests) have encountered great difficulties in their natural recovery (understood as being that which occurs without human intervention or action). Thus, as a condition to increase the resilience of systems, human intervention through the implementation of actions that contribute to increasing the resilience of systems must be seen as essential for the positive evolution of forest systems. In other words, all actions that contribute to the control and eradication of invasive species will allow the forest system to evolve in a balanced system, albeit artificially. However, this external help to the system—and above all, the possibility of these actions being continued (either from the perspective of control actions, or from the perspective of monitoring the system)—allow for an increase in the system's resilience.

As discussed in the previous section, the implementation of models for the optimization of actions to control and eradicate invasive species (such as *A. dealbata*) should preferably be framed in the management models of forest systems, and these systems should be capable of being agile enough to accommodate the new variables introduced by climate change. Forest management carried out adaptively, with the ability to adjust to variations—both from an environmental perspective and from the perspective of biological relationships—is capable of increasing the resilience of forest systems. The inclusion of new approaches to value available resources (as is the case of residual biomass resulting from actions to control and eradicate invasive species) must always be treated first from the perspective of optimizing existing resources and availability at a given location, and second, from the perspective of the recovery of (preferably) all byproducts (including generated waste), creating value chains. Therefore, adaptive forest management models are management models where the component of optimization of the resources used by the different processes and operations assumes a decisive role in their sustainability. In other words, with the optimization of resources, the effectiveness of operations is increased, which leads in turn to the efficiency of the processes.

The planning of the use of resources is done not only by taking into account the operations to be carried out, but also by considering all of those that can be reconciled on a broader scale (of a broader territorial type) where the displacement of resources is carried out to guarantee their permanence until the conclusion of the works. This planning avoids unnecessary transport of the means, reducing operational costs. On the other hand, this cost reduction can be used to boost other types of operations, such as actions to control and eradicate invasive species. Optimizing the available resources allows for greater availability of means, thus enhancing the capacity to act. This greater capacity to act is also reflected in a more significant contribution to increasing the competitive capacity and response of the species to be protected (whether they are part of a production forest or a conservation forest). This (artificial) aid increases the resilience of the forest system, as the increased pressure on invasive species weakens them and reduces their ability to recover and effectively compete with other species in the system. This also contributes to reducing the fuel load and, with it, the risk of rural fires. Thus, as fire is one of the leading causes that contribute to the dispersion of invasive species (mainly heliophyles and pyrophytes), this combination of actions increases the resilience of the forest system because it reduces the probability of fire occurrence. This allows the period between occurrences to increase and, thus, guarantees the recovery of the system, which together with the elimination of invasive species, does not suffer external competition and becomes stronger.

However, as mentioned in previous sections, and specifically with respect to the case of the national territory, the planning and optimization of resources to act in the forest system in a more comprehensive and extended manner are faced with constraints of a different nature the great majority of the time (if not all of the time). These constraints are directly associated with organizational and social issues. With regard to the latter, the processes of change in the demographic matrix of rural areas that have taken place in recent decades, with the migration of a considerable slice of the population to urban centers in search of better living conditions, have led to a slow process of, firstly, desertification, which has significantly reduced the population density in rural areas, and secondly, as the younger population left, in addition to the reduction in the population, there was abrupt ageing of the population, as the average age of the resident population started to be calculated without the presence of the younger sections of the population. The lack of financial resources to support operating costs—both of agricultural and forestry properties and to contribute to the management of common land—leads to the abandonment of the land. It is precisely in these territories that invasive species implantation has been verified and where fires have been reported more frequently.

The intricate mosaic of the succession of different types of occupation and land use, characterized by small plots, and characteristic of the landscape in the Norte, Centro, and Algarve, contrasts with the mosaic of the Ribatejo and Alentejo Regions, where large properties predominate.

This smallholding-estates dialectic, which gives the landscape a hue so characteristic of each of the regions, also represents one of the other major problems with the planning and organization of the most integrative and comprehensive management models and which is related to the ownership of property, as the organizational mosaic is owned by literally millions of owners, and in a considerable part of the rustic fractions (but mainly in the forest type), the owner of the property is not known due to the lack of registration. A comprehensive and integrative forest management model is intended to be implemented with the aim, in addition to supplying the most easily recoverable raw materials—as is the case of roundwood—of including actions of control and eradication of invasive species, or the control of woody forests. For example, it is faced with the need to counteract the difficulties imposed by the limits of small property and, above all, with the conciliation of the interests (wills) of the different owners. In Portugal, the process of grouping forest ownership dates back to the 1980s, as the first steps taken to counter some of the problems already identified always hampered the processes of optimizing forest management. In 2005, with the regulations presented in Decree-Law no. 127/2005, of 5 August, the regime for creating forest intervention zones (ZIFs) was established. As the summary of the decree-law itself states, the promotion of forest heritage management through the planning of forest operations and the promotion and support of associations is a way of establishing forestry operations with a dimension that allows for gains in efficiency in their management, through incentives for the grouping of farms for parceling, and disincentives for their division. In 2017, Decree-Law no. 66/2017, of 12 June, was passed to combat threats posed by harmful biotic and abiotic agents (i.e., pests) and the extent and recurrence of fires. Concerning the regulation of common land and other means of community production, Law no. 75/2017, of 17 August, revokes Law no. 68/93, of 4 September, with regard to common land and other community means of production owned and managed by local communities, integrated into the cooperative and social sector of the means of production. As an evolution of all of these legal diplomas presented, and with the assumption previously defined for forest spaces in the National Program for the Spatial Planning Policy (PNPOT) as territories to be valued, Resolution of the Council of Ministers No. of 24 June, where the concept of Integrated Landscape Management Areas (AIGP) is presented, was implemented. The sequence of legal frameworks made available in recent years aims to promote and implement more agile management models capable of responding to the new challenges posed by the current climate change scenario, which dramatically influences Portuguese forests.

The adoption of multifunctional models or joint forest management models aims to promote the adoption of shared measures and the optimization of existing resources. In this way, with the adoption of this type of model, the creation of value chains for, for example, residual biomass, originated in actions to control and eradicate invasive species, allowing this type of action to be integrated into the current operational plans of the management models, increasing the sustainability of the systems in all of their components. The final corollary intended to help implement these models is to adapt the national forest to the increasingly extreme scenarios caused by climate change (and its side effects). In other words, increasing the resilience of the Portuguese forests will allow them to react more consistently to externalities, ensuring that the resources recover and reestablish a balance.

6.4. Conclusions

The impacts of climate change on the Portuguese forests have been felt in several respects, both directly and indirectly, from which specific environmental parameters can be highlighted, with significant variability. This set of impacts is caused by the trends that have been shown—firstly, for the increase in average air temperature, for the reduction in precipitation, and for the concentration of precipitation periods, which lead, secondly, to secondary effects that are directly derived from the former, such as the increased risk of rural fires and the dispersion of invasive species. All of these impacts—direct or indirect—associated with the abandonment of rural areas affect the forest and imply that new strategies should be defined in the form of management models that allow an evolution towards increasing the resilience of forest territories.

In the set of problem questions presented at the beginning of this work, the first question expressed the need to identify how climate change can cause variations in the environmental conditions prevailing in forest systems and how these changes alter the evolution of these systems. As confirmed in the course of the work carried out, changes in parameters such as average air temperature and precipitation—associated with changes in seasonality and the distribution of periods of occurrence of this precipitation—have led to the recurrence of periods of drought, with significant direct effects on the forest. This situation has contributed to the increase in the risk of rural fires, contributing to once again weakening the forest, mainly as a result of the increase in the recurrence of these same fires, which have begun to occur with increasingly shorter time intervals, not allowing for the natural recovery of forest stands. However, fires have allowed and contributed to the dispersion of invasive species of the heliophyle and pyrophyte type, acting as a species-selection agent that gives a competitive advantage to invasive species. This situation has created a vicious circle whereby fire destroys the forest, opening the way for the establishment of invasive species that, in turn, contribute to the accumulation of large combustible loads, enhancing the frequency of new occurrences of fire.

This circle is harmful to the resilience of the forest and encourages the application of actions that contribute to the reduction/mitigation of these negative impacts, which is precisely the point of the second problem question presented. This time, supporting the sustainability of actions to control and eradicate invasive species in the creation of value chains can be a way forward, as one of the great difficulties faced by these actions (and their continuity) has precisely to do with the costs associated with their execution and recurrence. In other words, any form of recovery and valuation of (waste) products resulting from the actions of control and eradication of invasive species can contribute to supporting the costs (or part of them) associated with the control of invasive species, allowing such actions to be carried out until the desired results have been obtained, i.e., the artificial elimination of these species, giving the necessary time for the native species (or species planted with economic interest) to recover. The energy recovery of the biomass resulting from the control and eradication operations of species such as *A. dealbata* has shown to be a possibility to be considered, mainly because it allows for the recovery of large amounts of residual biomass. In this way, constant pressure is created on the stands of invasive species, reducing their ability to recover.

Anticipating the effects of climate change, it is necessary to present forest management models that, on the one hand, allow for a better and greater appreciation of the forest resources while, on the other hand, simultaneously allowing the creation of a more resilient forest. It is essential to discuss and present a strategy to be defined for the models that enable a response to the challenges that the Portuguese forests will undoubtedly face in the future. In this way, and following the third problem question presented, the present work highlights the adaptive multifunctional models as those that will be able to better contribute to the increase in the resilience of the forest, as they are dynamic models, where decision making on the measures to be implemented is based on the assumption that forest management must be comprehensively framed and include the analysis of all variables, so that the resource is not only valued, but enhanced.

As a corollary, it can be concluded that climate change has significant impacts on the variability of the environmental parameters that regulate the evolution and development of the Portuguese forests and that the implementation of measures such as the control of invasive species, supported by the creation of chains of value—in this case, through energy recovery—can contribute to increasing the resilience of the forests. The adoption of dynamic, adaptive, and multifunctional management models contributes to increasing the value of the resources, giving them other perspectives such as ecosystem services, which include the mitigation of climate change (by capturing and sequestering carbon), and where true circular bioeconomy and sustainable rural development approaches are now included.

6.5. Limitations of the Study

Any study or research process, however well-structured it may have been before its beginning, is faced with imponderables that may require changes in the course or changes in the objectives to be achieved. During the present investigation, some situations also arose that impacted the course of the work and forced the application of new strategies and methodologies.

The COVID-19 pandemic was undoubtedly the main obstacle to the development of this work, particularly with regard to some fieldwork, which was intended to complement the work started in 2018 and which lasted until 2019, where the confinement that started in March 2020 made it impossible to collect more samples, which would have allowed us to obtain the number of samples needed to build the growth model for *A. dealbata*. When field activity resumed, with an interval of two years, all stands in the study area had been cut in operations to clean and control invasive species throughout the region. This made it impossible to find specimens older than 20 years of age that would allow for validation of the growth behavior of trees aged older than 20 years.

However, despite the difficulties experienced during the pandemic, it was possible to carry out the practical work of laboratory characterization of the biomass samples, which, although carried out intermittently, was completed without significant constraints. The work of dendrometric characterization of the samples was also concluded, except in this case because the samples were not collected in the amounts initially foreseen.

As the most significant difficulty experienced during the completion of this work, the impossibility of ensuring direct personal contact between the participants in the work (i.e., candidates and supervisors) for a significant part of the time must be highlighted, as it is understood that face-to-face contact provides a greater possibility of enriching the discussions and a greater depth of the themes. There were also many open questions, which we intend to continue to develop and answer in future work since the themes, as extensive and complex as they are, justify greater depth and dedication.

6.6. Future Work

The conclusion of this work does not mean the end of the theme or themes discussed here. On the contrary, the work developed serves to open up a set of possibilities for future research related to the topics addressed, but for which it is intended to give a new impetus.

Among the topics addressed, climate change will certainly be the impetus for continuing the research. Thus, if in the present work the study of climate change was limited only to its effects, we now intend to analyze the impact that climate change is having on the development of some species through the establishment of growth models for invasive woody species, such as *A. melanoxynon*, *Robinia pseudoacacia*, *Gleditsia triacanthos*, or *Ailanthus altissima*. We also intend to complete the growth model of *A. dealbata* initiated in the present study, as due to the impossibility of collecting specimens older than 20 years, this is understood to have not been fully developed.

We also intend to establish a model of correlation between the growth of some woody species and parameters such as precipitation and temperature, which can serve as a model to characterize the climate in locations where data are not available—for example, due to the complete absence of a historical record—or to analyze periods prior to the possibility of recording data.

We also intend to continue to analyze forest management models, mainly in identifying processes for the recovery of residual biomass to its full potential but giving preferential focus to energy recovery through thermochemical conversion processes, such as torrefaction, pyrolysis, or gasification, combined with the analysis of forest-based supply chains, from a perspective of resource sustainability and the introduction of circular bioeconomy practices.

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