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Assessment of the Portuguese Forest Potential for Biogenic Carbon Production and Global Research Trends

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Abstract

Forests play a central role in climate change mitigation by acting as biogenic carbon reservoirs and providing renewable biomass for energy systems. In Portugal, where fire-prone landscapes and species composition dynamics pose increasing management challenges, understanding the carbon storage potential of forest biomass is crucial for designing effective decarbonization strategies. This study provides a comprehensive characterization of the Portuguese forest and quantifies the biogenic carbon stored in live and dead biomass across the main forest species. Species-specific carbon contents, rather than the conventional 50% assumption widely used in the literature, were applied to National Forest Inventory data, enabling more realistic and representative carbon stock estimates expressed in kilotonnes of CO_2 equivalent. While the approach relies on inventory-based biomass data and literature-derived carbon fractions and is therefore subject to associated uncertainties, it provides an improved representation of species-level carbon storage at the national scale. Results show that *Pinus pinaster*, *Eucalyptus globulus*, and *Quercus suber* together represent the largest share of carbon storage, with approximately 300,000 kilotonnes of CO_2 equivalent retained in living trees. Wood is the dominant carbon pool, but roots and branches also account for a substantial fraction, emphasizing the need to consider both above- and below-ground biomass in carbon accounting. In parallel, a bibliometric analysis based on the systematic evaluation of scientific publications was conducted to characterize the evolution, thematic focus, and geographic distribution of global research on forest-based biogenic carbon. This analysis reveals a rapidly expanding scientific interest in biogenic carbon, particularly since 2020, reflecting its growing relevance in climate change mitigation frameworks. Overall, the results underscore both the strategic importance of Portuguese forests and the alignment of this research with the broader international scientific agenda on forest-based biogenic carbon.

Keywords: forest biomass; biogenic carbon; species-specific carbon accounting; Portugal; bibliometric analysis

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1. Introduction

Energy plays a central role in the sustainability of Portuguese, European, and global economies. Although fossil fuels were long considered sufficient to meet energy needs, population growth and the increasing energy intensity of modern societies have led to a significant rise in demand [1]. The associated emissions and environmental impacts have heightened social and environmental concerns, driving the development and deployment

of alternative and renewable energy sources [2]. Despite the growing contribution of renewables, fossil fuels remain the dominant component of the global energy mix, still accounting for more than two-thirds of total primary energy consumption, while renewable sources such as biomass and waste represent a significant share of the remaining fraction [3,4]. Even under ambitious climate change mitigation scenarios, fossil fuels are expected to persist as part of the energy system in the coming decades [5]. In this context, forests emerge as one of the most relevant natural systems capable of mitigating energy-related emissions through biogenic carbon sequestration.

Carbon dioxide (CO_2) is the main contributor to global greenhouse gas emissions, largely driven by energy-related activities. Human intervention in the carbon cycle, particularly through the combustion of fossil fuels, has led to a rapid increase in atmospheric CO_2 concentrations [6,7], intensifying climate-related risks such as extreme weather events, droughts, and heat waves [8].

Carbon is a fundamental element for life on Earth and forms the basis of all ecosystems, with relevance extending beyond chemistry and biology to areas such as energy, climate, and industrial systems [9]. Within the natural carbon cycle, carbon circulates between the atmosphere, biosphere, lithosphere, and hydrosphere. Unlike fossil carbon, which is released after being stored over geological timescales, biogenic carbon is part of a fast cycle, continuously exchanged between the atmosphere and living organisms [10,11]. Forest ecosystems are central to this process, as they act as major sinks of atmospheric CO_2 through photosynthesis, storing carbon in living biomass, dead organic matter, and soils [12].

Forests are the primary source of biomass [13]. Their socioeconomic importance is significant, especially in rural areas where their presence is essential for regional development. Furthermore, forests play a crucial role in true carbon storage and, therefore, stimulating their controlled growth can enable, among other benefits, the reduction of CO_2 levels in the atmosphere [14].

The quantification of forest carbon stocks is a critical aspect of national and international carbon accounting frameworks. However, current methodologies often rely on simplified assumptions. One of the most widespread practices is the use of a uniform carbon fraction of 50% of dry biomass, as recommended by international guidelines such as those of the IPCC (Intergovernmental Panel on Climate Change) [15]. While this assumption facilitates reporting and comparison, it overlooks the well-documented variability of carbon content across tree species, biomass components, stand ages, and site conditions. Recent studies indicate that such variability can be particularly relevant in heterogeneous forest systems, potentially leading to biased estimates of carbon stocks at regional and national scales [16,17].

Mediterranean forest ecosystems, in particular, present specific challenges for forest carbon accounting. These systems are typically characterized by a variety of species with contrasting growth patterns and biomass allocation, combined with a high frequency of disturbances [18]. Portugal represents a paradigmatic case within this context. Portuguese forests are dominated by species such as maritime pine (*Pinus pinaster*), eucalyptus (*Eucalyptus globulus*), cork oak (*Quercus suber*), holm oak (*Quercus ilex*), stone pine (*Pinus pinea)* and extensive shrubland areas, resulting in a highly heterogeneous landscape [19]. Moreover, forest management practices, land abandonment, and climatic conditions have contributed to an increased incidence of wildfires, which strongly influence carbon dynamics.

Wildfires act as a major driver of carbon fluxes in Portuguese forests by rapidly transferring carbon from biomass pools to the atmosphere. The severe fire season of 2017, for example, resulted in emissions of approximately 21.5 million tonnes of CO_2 equivalent, representing a substantial fraction of national annual emissions [20]. Beyond immediate

emissions, recurrent fires affect forest structure, species composition, soil properties, and long-term carbon storage capacity [20,21].

Forest residues generated through forest management represent both a challenge and an opportunity. On the one hand, the accumulation of residues increases fire risk; on the other hand, these materials constitute a valuable resource for energy production and other bioproducts, potentially contributing to decarbonization efforts while enhancing forest resilience [22,23]. Effective forest management strategies can therefore simultaneously support fire prevention, economic sustainability, and climate change mitigation [23].

Despite the widespread recognition of forests as key reservoirs of biogenic carbon, national-scale forest carbon accounting still relies heavily on simplified methodological assumptions. In the Portuguese context, this limitation is accentuated by the dominance of tree species with contrasting growth patterns, the frequent occurrence of wildfires, and the reliance on national forest inventory data for carbon reporting. Although previous studies have addressed forest biomass and carbon stocks [19], comprehensive national-scale assessments that explicitly integrate species-specific carbon contents into inventory-based biomass data, while simultaneously accounting for both above- and below-ground biomass pools, remain limited. The present study addresses this gap by applying species-specific carbon contents derived from the literature to updated National Forest Inventory data, thereby producing more realistic and transparent estimates of biogenic carbon storage in Portuguese forests. By explicitly examining how the choice of carbon fraction influences national carbon stock estimates and species-level contributions, this work advances current forest carbon accounting practices and provides a more robust scientific basis for forest management and carbon reporting.

In addition to the national-scale quantitative assessment, this study includes a bibliometric analysis aimed at characterizing the evolution and current state of international research on forest-based biogenic carbon. Rather than constituting an independent objective, the bibliometric component is used as a complementary tool to assess the maturity of the field, dominant research themes, and geographic patterns of scientific production.

A preliminary screening of the literature indicates a marked acceleration in publications on biogenic carbon since 2020, including a rapidly growing subset focused on forest biomass, underscoring the timeliness and relevance of national-scale assessments.

By assessing these trends, the analysis provides a broader scientific context in which national forest carbon assessments can be interpreted, without implying direct quantitative comparisons between countries. The bibliometric analysis is therefore intended to contextualize the study within current global research trends and does not form part of the carbon stock calculation framework.

2. The Global and European Forest

In 2021, forests covered 31% of the world's land area, totaling 4.06 billion hectares [24]. Despite their global extent, forest systems differ markedly in structure, management intensity, and carbon dynamics [18]. About half of these forests remain largely undisturbed, and only around one-third are classified as primary forests, which are naturally regenerated and minimally impacted by human activity. Currently, 93% of the world's forests are naturally regenerating (including both primary and secondary forests), while the remaining 7% are planted [25].

More than half of the world's forests are located in just five countries: Russia, Brazil, Canada, the United States of America, and China, highlighting the uneven geographical distribution of global forest resources [25]. Since 1990, the world has lost 178 million hectares of forest, mostly due to deforestation [26]. During this time, the area of naturally regenerating forests has decreased, while the area of planted forests has increased by

123 million hectares [25]. Of the 7% of planted forests, about 45% are intensively managed areas, usually consisting of one or two tree species of the same age, planted for production purposes. Europe has the lowest proportion of forest plantations of any continent, at just 6%, while South America has the highest, at 99% [26].

From a carbon perspective, these forests naturally exhibit substantial differences. Boreal forests generally store large amounts of carbon in soil and below-ground biomass and exhibit long carbon residence times, while temperate forests tend to accumulate higher above-ground biomass with relatively stable carbon stocks [27]. In contrast, Mediterranean forest systems are characterized by lower biomass densities, higher allocation to below-ground structures, and frequent disturbances, particularly wildfires, which strongly influence carbon turnover rates [18]. Consequently, generalized global forest statistics may not adequately capture the variability of biogenic carbon dynamics across different forest types.

Europe presents a distinctive case within this global context. Over the last three decades, Europe's forest area has grown by 9%, currently encompassing 227 million hectares, meaning that more than one-third of Europe's total land area is covered by forests. About 46% of the European forests consist mainly of coniferous trees, 37% primarily feature broadleaved trees, and the remaining forests are mixed. Introduced tree species play a minor role in European forestry, comprising only 3.1% of the total forest area [28].

In the European Union, forests covered around 159 million hectares in 2021, representing an increase of almost 10% compared to the 145 million hectares recorded in 1990 [29].

Portugal exemplifies many of these European trends while also exhibiting characteristics specific to Mediterranean forest systems. Portuguese forests are dominated by species with contrasting growth patterns and management regimes, including fast-growing plantations and extensive shrubland areas [30]. Combined with frequent wildfire occurrence, these features make Portuguese forests particularly sensitive to methodological assumptions in forest carbon accounting.

3. The Portuguese Forest

Portugal, located in Southwestern Europe, covers a territory of 92,212 km^2 [31]. The areas referred to as forestry, which includes forest, scrubland, and unproductive land, cover an area of 6.2 million hectares, corresponding to approximately 69.4% of the Portuguese mainland [19]. Figure 1 illustrates the distribution of forest and bushland cover in mainland Portugal, with forests marked in dark green and bush areas in light green.

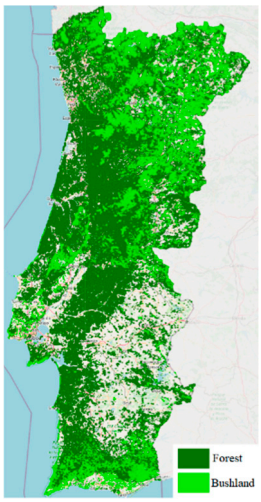


Figure 1. Spatial distribution of forest and shrubland areas in mainland Portugal, based on national land cover data [32].

Approximately 85.5% of the forest area in Portugal is privately owned, with the remaining 14.5% under public ownership. Specifically, 2.7% of the forests are state-owned, while 11.8% are managed by local communities [33]. The Portuguese forest includes some of the most significant tourist resources in the country, namely the Buçaco National Forest, Pena Park, and the Laurissilva Forest of Madeira [34].

The Institute for Nature Conservation and Forests (ICNF) began the process relating to the National Forest Inventory (NFI) in 1963. The first report of this inventory, NFI 1, was released in 1965. Since then, the inventory has been continuously updated, with new editions published approximately every ten years. The most recent edition, the 6th Inventory (NFI6), was published in 2019 [35]. In 2018, forests, including wooded areas and those temporarily without tree cover due to logging, fires, and regeneration, represented the primary land use in Portugal, covering 38.8%, corresponding to 3.4 million hectares. The remaining territory was occupied by agriculture-based land (26.2%), bush (12.4%), agroforestry systems (8.2%), pastures (6.4%), and artificial territories (5.2%). The remaining land use categories, including surface water bodies, bare or sparsely vegetated areas, and wetlands, jointly accounted for approximately 2.8% of the national territory [36].

Of the five territorial units of mainland Portugal, the Central region has the largest forest area, covering approximately 1.4 million hectares, representing 50% of its territory in 2018. Alentejo is the second region with the largest forest area, covering around 1 million hectares and representing 31.6% of its territory. It is followed by the North region, with a forest area of 788 581 hectares (37%), and the Algarve region, with 171 319 hectares (34.3%). The Lisbon Metropolitan area has the smallest forest area in mainland Portugal, covering only 73,964 hectares, representing 24.5% of its total area [32].

A large part of the forest area, about 2.3 million hectares, is used for silvopastoral purposes. The main indigenous animal breeds, such as the black pig and mountain cattle, rely on these forest areas [34].

3.1. Historical Evolution

As expected, the Portuguese territory's forest area and species distribution have changed over the last few years. Figure 2 illustrates the evolution of the total forest area and the individualized areas of occupation of the main forest species in Portugal between 1875 and 2015.

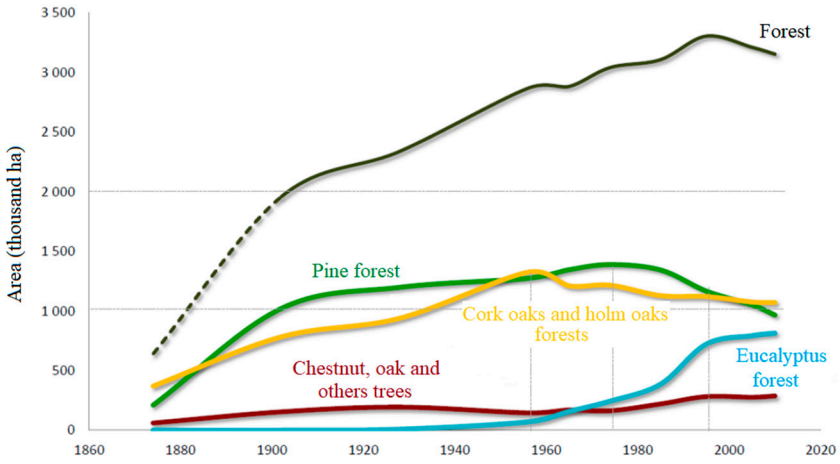


Figure 2. Historical evolution of forest area in Portugal by major forest types between 1875 and 2015 [37].

An analysis of the previous figure reveals a general trend of increasing forest area over time, with the total forest area growing steadily, particularly from the 1920s until the 1990s. According to Food and Agriculture Organization of the United Nations [38],

between 1990 and 2015, Portugal was the only country in the European Union that recorded a decrease in its forest area, suffering a loss of 254,000 hectares during this period. However, this trend was reversed, as the latest National Forest Inventory (NFI 6) recorded an increase of 60,000 hectares (1.9%) in forest area compared to the previous evaluation in 2010 [19]. Of particular note are the cork and holm oak forests, which cover around 1 million hectares and represent one-third of the forest area. These are multiple-use ecosystems that do not focus primarily on wood production. Next are the pine forests, with an area of around 1 million hectares, which have faced significant reductions due to wildfires and pests such as the pine wood nematode [39].

Although deciduous hardwoods are the least representative in terms of area, they have shown a systematic increase in the last 20 years, especially between the last two inventories (2005 and 2015), with a growth of 46,000 hectares (17%). On the other hand, eucalyptus forests cover 845,000 hectares, approximately 26% of the continental forest, and have continuously increased over the last 50 years [19].

Portuguese forests are also characterized by a significant presence of invasive and weedy species, mainly shrubs. The most common shrub species include brooms (*Cytisus* spp.), gorse (*Ulex* spp.), and brambles (*Rubus* spp.) [19]. The shrublands and spontaneous pastures cover approximately 2.3 million hectares of the Portuguese territory [40]. In some situations, the shrub species may also be considered weeds. Weedy species, which can be native or exotic, are defined as plants that interfere with human activities and are considered undesirable in their current location [41]. As for invasive species, they are non-native, with a high potential for spread and easy reproduction [42]. These species can significantly modify ecosystems if not adequately controlled, impacting local biodiversity and creating unfavorable environmental conditions [43,44]. The presence of invasive species is consistent across continental territory, with acacias, hakeas, reeds, and beach she-oaks being the most frequently occurring species [19]. Nevertheless, the acacia genus is the most predominant [45].

3.2. Characterization

According to the 6th National Forest Inventory (NFI6), native species predominate in the composition of Portuguese forests, covering 72% of the total forest area [19].

The distribution of the Portuguese continental forest can be categorized into four main groups [19]: (i) pine forests-predominantly composed of maritime pine (*Pinus pinaster*) and stone pine (*Pinus pinea*); (ii) evergreen broadleaves-dominated by cork oak (*Quercus suber*) and holm oak (*Quercus ilex*); (iii) deciduous hardwoods-including oaks (*Quercus* spp.), chestnut trees (*Castanea* spp.), and other species; and (iv) eucalyptus forests-consisting mainly of eucalyptus (*Eucalyptus* spp.).

The infographic in Figure 3 illustrates the main forest species found in Portugal and their percentage distribution in 2015.

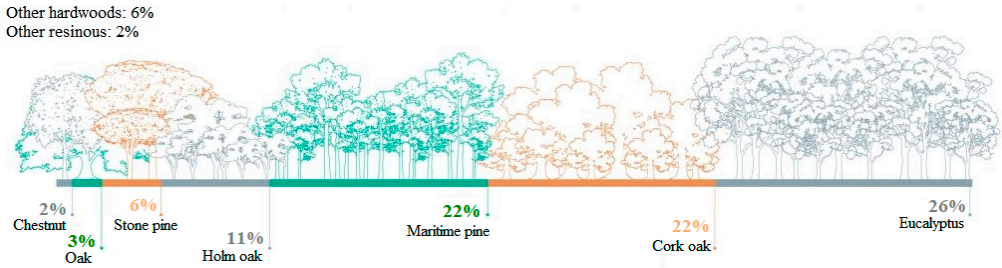


Figure 3. Distribution of continental forest area in Portugal by dominant forest species in 2015 [46].

The dominant species in the Portuguese forest is eucalyptus, occupying 26% of the total forest area, followed by maritime pine and cork oak, each accounting for 22%. Holm oak represents 11% of the forest area, while stone pine covers 6%. Oaks and chestnut trees are the species that present the smallest occupation area, each covering only 2% of the forest area. However, other species, such as carob trees and acacias, also represent a significant portion of the Portuguese forest, occupying approximately 16,400 and 8400 hectares, respectively [19]. Other hardwood species cover around 6% of the total forest area, while the remaining resinous species, besides maritime pine and stone pine, represent 2% of the total area.

Naturally, the species' occupation areas have changed over the past few years. Figure 4 illustrates the evolution of the total occupancy areas of the primary forest species in Portugal between 1995 and 2015.

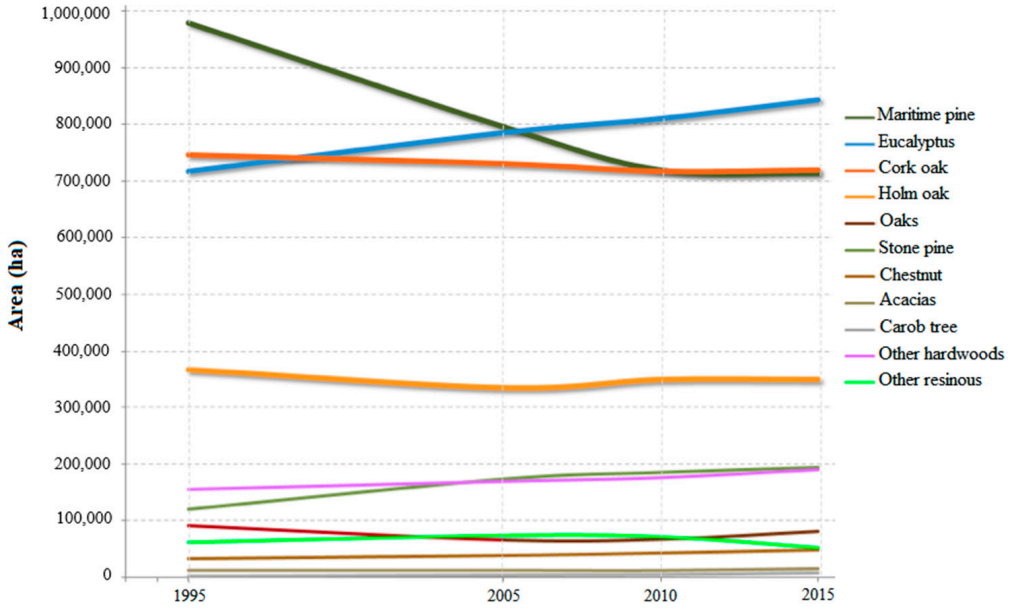


Figure 4. Temporal evolution of forest area in Portugal by major tree species between 1995 and 2015 [19].

Maritime pine, eucalyptus, and cork oak have been the most abundant species in Portugal's forests since records began, showing significant variation in their areas over time. Unquestionably, the most important change in occupation was experienced by maritime pine, with a reduction of approximately 265,000 hectares. This decrease was most pronounced between 1995 and 2010, with an annual decline of 1.8%. The main reasons for this reduction are forest fires and the pests that have affected the pine forests, especially the *Pinus pinaster* species [19]. On the other hand, eucalyptus has progressively increased its occupation area by 127,800 hectares between 1995 and 2015. As for the cork oak, there was a reduction of 26,900 hectares over the same period. As for the other species, their occupation area has not changed considerably. However, it is essential to note that stone pine and other hardwoods increased their areas of occupation by 73,400 and 35,000 hectares, respectively.

4. Availability Assessment of Forest Biomass in Portugal

Considering that the characterization of the Portuguese forest was covered in the previous chapter, it is now essential to quantify the availability of forest biomass. Therefore, this chapter focuses on the detailed analysis of the amount of biomass present in different species and components of the forest, providing an estimate of its potential for energy production.

The EU Directive 2018/2001 defines biomass as the "biodegradable fraction of products, waste, and debris of biological origin from agriculture, including substances of plant and animal origin, forestry and related industries, including fishing and aquaculture, as well as the biodegradable fraction of industrial and urban waste of biological origin" [47].

According to its origin, forest biomass can be classified into primary and secondary. Primary forest biomass is generated directly from the forest. It can comprise residues from forestry activities (maintenance operations, thinning, or deforestation), material from actions to control invasive species, and trees attacked by pests and diseases [48]. Secondary forest biomass consists of residual organic matter (sawdust, retests, black liquors, clippings, and chips) from wood industry by-products and other residues from wood processing [48,49].

The global annual production of lignocellulosic biomass, including agricultural and forest residues and organic solid waste from recycling stations, paper, wood, and pulp, is estimated to be around 181.5 billion tonnes [50]. Biomass and waste together account for 9.4% of primary energy consumption globally. In the EU-27, bioenergy remains the primary renewable energy source, contributing 59% of the total renewable share in 2021, with 27% of this biomass derived from forestry [51]. The countries with the highest absolute bioenergy consumption are Germany, France, Italy, and Sweden [52]. In 2020, EU forests were estimated to have a total above-ground living biomass stock of around 18.4 million tonnes of dry matter, equating to 117 tonnes per hectare. Although the northern EU has a larger forest area, the central region, particularly Germany, France, and Poland, has the most significant biomass stocks [53].

In Portugal, biomass accounts for 15.8% of primary energy consumption, with the domestic and service sectors and the pulp and paper industries being the primary users [54]. However, current information on forest biomass use for energy in Portugal is complex and often unclear due to several factors. In the residential sector, biomass typically comes from informal markets or self-supply, making it challenging to obtain accurate data. Furthermore, industries that process agricultural and forestry products often use biomass resulting from their activities. Although estimated quantities are reported due to mandatory environmental regulations, specific details about the types of biomass used are often lacking [34]. These factors create ongoing challenges in monitoring and managing forest biomass utilization in Portugal.

The potential production of forestry residues in a given region is directly related to the species present and the extent of their occupied areas, with this evaluation relying on the forest residue production coefficients of the species [55]. To accurately assess the availability of forest biomass and residues, forest inventories, geographic information systems (GIS), and remote sensing technologies are employed [56]. These tools provide a foundation for forest biomass estimation, which can be conducted using direct and indirect methods [57]. Direct methods, although more expensive and time-consuming due to their destructive sampling process, offer higher accuracy by determining the dry weight of all biomass components, including the stem, bark, and sometimes even the roots [56,58].

In Portugal, the ICNF conducts a detailed assessment of national forestry resources by collecting data from aerial images and conducting on-ground vegetation measurements. The process is divided into three phases. The first phase involves using aerial imagery to visually classify and evaluate the area of different land use and land cover classes. In the second phase, ground vegetation, primarily forests and shrublands, is characterized through measurements and observations taken using various sampling methods in the field. The third phase includes soil sampling from a subset of the field-visited plots. Biomass and associated carbon estimates reported by the ICNF are based on these inventory data and the underlying allometric formulation [59].

The biomass potential estimates conducted by ICNF cover both live and dead biomass. Live biomass includes the trees (above-ground biomass and roots) and the undergrowth, which refers to the vegetation growing beneath the canopy of adult trees. This undergrowth includes shrubs, herbaceous plants, and natural regeneration that coexist within forested areas and are measured as part of the National Forest Inventory [19]. Dead biomass, on the other hand, encompasses standing trees, fallen trees, stumps, and leaves.

All biomass quantities reported in this section are derived directly from the Portuguese National Forest Inventory [19], which applies standardized allometric models, biomass expansion factors, and conversion coefficients validated at the national level. The present study does not re-estimate biomass components but uses official inventory data for subsequent carbon stock calculations.

Table 1 provides an overview of the available live biomass in Portugal, categorized by species. The data includes both trees biomass and undergrowth and are expressed in kilotonnes (kt) of dry matter. The values presented correspond to national-level estimates aggregated over a reference forest area of approximately 3.4 million hectares, according to the National Forest Inventory.

Table 1. Available live forest biomass by species in Portugal (dry matter) [19].

Species	Trees [kt]	Undergrowth [kt]
Maritime pine	44,980	3920
Eucalyptus	34,710	4610
Cork oak	34,290	3200
Holm oak	9800	1340
Oaks	7230	360
Stone pine	9250	810
Chestnut tree	8090	150
Carob tree	620	70
Acacias	2600	30
Other hard woods	11,280	880
Other resinous	3640	220
Total	166,490	15,590

The total biomass, combining trees and undergrowth, amounts to 182,080 kilotonnes of dry matter, with the majority coming from tree biomass (166,490 kilotonnes). This data highlights the dominant role of maritime pine, eucalyptus, and cork oak in Portugal's forest biomass and underscores the potential of these species for energy production and other uses. Maritime pine has the highest biomass among the listed species, with 44,980 kilotonnes in trees and 3920 kilotonnes in undergrowth, indicating a significant presence and potential for biomass production. Eucalyptus is the second most abundant, contributing 34,710 kilotonnes in tree biomass and 4610 kilotonnes in undergrowth, reflecting a dense understory vegetation. Cork oak also contributes notably to Portugal's live biomass, with 34,290 kilotonnes in trees and 3200 kilotonnes in undergrowth.

The composition of trees varies according to the species, but, in general, they are made up of wood, bark, leaves, branches, and roots. This division applies specifically to trees, since the heterogeneous and short-stature nature of undergrowth makes such component-based categorization impractical. Table 2 presents the living biomass per tree component for the main forest species found in the Portuguese forest.

For some species, specific biomass components (e.g., bark and leaves) are not individually reported in the Portuguese National Forest Inventory. In these cases, the corresponding values appear as zero in Table 2 and should be interpreted as "not available" data rather than as an absence of biomass.

Table 2. Living biomass per tree component in Portugal (dry matter) [19].

Species	Wood [kt]	Bark [kt]	Leaves [kt]	Branches [kt]	Roots [kt]
Maritime pine	22,380	5050	2440	5380	9730
Eucalyptus	18,810	3210	2670	3070	6930
Cork oak	18,520	5450	1060	5030	4210
Holm oak	2870	970	0	1770	4200
Oaks	3080	0	300	2220	1640
Stone pine	2230	310	290	6100	320
Chestnut tree	1120	280	340	410	6110
Carob tree	100	0	0	270	250
Acacias	950	180	160	270	1040
Other hard woods	5320	0	410	3320	2230
Other resinous	1780	400	210	470	790
Total	77,160	15,850	7880	28,310	37,450

As mentioned, maritime pine contains the most significant amount of living biomass, particularly in the wood component, along with significant amounts of bark and roots. In the literature, wood is commonly classified as a high-value biomass fraction, typically prioritized for material applications such as furniture and pulp production, while non-wood components (e.g., bark, branches, leaves, and roots) are more frequently considered suitable for energy recovery, particularly when derived from forest management operations [60,61].

Across all forests species, the total living biomass associated with these "non-wood" components is estimated at 89,490 kilotonnes of dry matter, representing approximately 54% of the total available living biomass [19].

While living biomass constitutes the most considerable fraction of energy use, it is also important to consider dead biomass, which offers additional, albeit smaller, potential. Table 3 presents the available dead biomass by species, including standing trees, fallen trees, stumps, and leaves.

Table 3. Available dead forest biomass by species (dry matter) in Portugal [19].

Species	Standing Trees [kt]	Fallen Trees [kt]	Stumps [kt]	Leaves [kt]	Total [kt]
Maritime pine	920	200	111	24	1255
Eucalyptus	330	220	152	27	729
Cork oak	390	70	11	5	476
Holm oak	160	20	1	1	182
Oaks	50	0	8	3	61
Stone pine	40	20	5	4	69
Chestnut tree	840	0	2	1	843
Carob tree	0	0	0	0	0
Acacias	100	0	1	0	101
Other hard woods	70	150	19	7	246
Other resinous	30	10	4	1	45

Among the species, Maritime pine has the highest total dead biomass, totaling 1255 kilotonnes of dry matter, followed by chestnut tree with 843 kilotonnes and eucalyptus with 729 kilotonnes. Other species, such as cork oak, holm oak, oaks, and other hardwoods, contribute smaller amounts. In total, dead biomass accounts for 4007 kilotonnes of dry matter in the Portuguese forest.

Although often overlooked, dead biomass can still represent a modest yet valuable resource for renewable energy production, particularly in fire-prone or unmanaged forest areas. Its accumulation, if not properly managed, may increase the risk of wildfires and lead to additional carbon losses through natural decay or uncontrolled combustion.

Despite their recognized potential, both live and dead biomass are often evaluated differently across studies, contributing to significant discrepancies in national availability estimates. When expressed on an area basis, the live biomass stock reported by the National Forest Inventory corresponds to approximately 54 t/ha, which is consistent with values reported for Mediterranean forest systems, although lower than the EU average. This reflects structural, climatic, and management differences between Mediterranean and temperate or boreal forests [53].

This becomes evident when comparing values reported by different Portuguese sources: the APA [34] estimates a potential of 2.2 million tonnes per year, while according to Cunha and Marques [62], the theoretical annual potential is approximately 2.0 million tonnes. In contrast, the National Plan for the Promotion of Biorefineries suggests a lower value of 1.5 million tonnes per year [63]. These differences can be attributed to the use of different methodologies and criteria in each assessment, such as forest inventories, remote sensing, or GIS-based models [56,57]. The scope of the biomass considered can also vary. While some estimates include only primary forest residues, others incorporate agricultural by-products, industrial waste, or spontaneous vegetation [48,49]. Additionally, factors such as biomass collection efficiency, regional and seasonal variation, spatial coverage, and assumptions about technical or economic feasibility can significantly influence the results [13,50]. While the exact methodologies used in the previously referenced studies are not fully detailed in the public domain, these known sources of variation help explain the divergence between the estimated values. Altogether, these complexities highlight the challenges in accurately determining the biomass available for energy production.

5. The Role of Portuguese Forests in Biogenic Carbon Sequestration

In the context of global decarbonization strategies and growing concerns about climate change, the role of biological systems in carbon sequestration has been receiving increasing attention. Among them, forests represent one of the most important natural mechanisms for capturing and storing the atmospheric carbon [64].

5.1. The Carbon Cycle and the Role of Natural Reservoirs

As previously mentioned, the carbon cycle is a fundamental Earth system process in which carbon circulates between the atmosphere, oceans, biosphere, and geosphere [10]. It is typically divided into two interconnected subsystems: the fast (or short-term) cycle and the slow (or long-term) cycle. The fast cycle governs the continuous exchange of carbon between the atmosphere, terrestrial biomass, and the oceans, operating over several years to decades. In contrast, the slow cycle involves carbon stored in geological formations such as sedimentary rocks and fossil fuels, evolving over millions of years [65].

Forests, as major biological systems, play a critical role in this cycle by absorbing atmospheric CO_2 through photosynthesis and storing it in woody biomass, roots, leaves, and soils. This process effectively removes carbon from the atmosphere, contributing to climate regulation and offsetting anthropogenic emissions [66,67].

In this context, it is important to distinguish between live and dead biomass within forest ecosystems. Live biomass functions primarily as a carbon sink, absorbing CO_2 from the atmosphere and storing it through growth [68]. In contrast, dead biomass tends to act as a source of emissions, releasing CO_2 back into the atmosphere through decomposition [69]. This dynamic illustrates how forests simultaneously serve as both carbon reservoirs and emission sources within the fast carbon cycle, depending on the state and turnover of biomass components.

However, human activities have increasingly accelerated the transfer of carbon from the slow to the fast carbon cycle. While the combustion of fossil fuels remains the dominant

driver, other practices, such as deforestation, intensive agriculture, the production of cement and land-use change, also contribute significantly to this shift [70]. These processes introduce large quantities of previously sequestered carbon into the active atmosphere, biosphere, and ocean system, disrupting the natural balance, as illustrated in Figure 5.

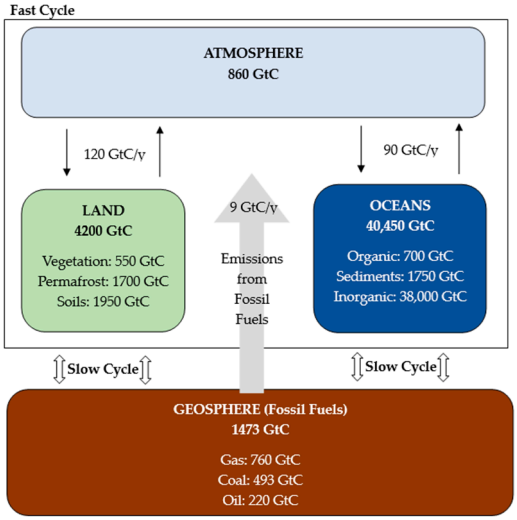


Figure 5. Schematic representation of the fast and slow carbon cycles, illustrating carbon transfer between geological and biological reservoirs. Data from [66].

As illustrated in Figure 5, the fast carbon cycle includes three major interconnected pools: the atmosphere, terrestrial ecosystems (land) and the oceans. Natural fluxes continuously move carbon between these pools, for example, photosynthesis transfers atmospheric CO_2 into vegetation, while respiration and decay return carbon to the atmosphere. These exchanges are relatively balanced over short timescales. In contrast, the geosphere, shown at the bottom of the figure, contains fossil carbon (gas, coal and oil) stored over millions of years. Under natural conditions, this carbon would remain locked away for geological timescales. However, human activity has introduced a new, unbalanced flux (grey arrow), transferring carbon from the slow cycle to the fast cycle through fossil fuel combustion. This artificial flow adds over 9 gigatonnes of carbon per year to the atmosphere, significantly perturbing the natural carbon balance and increasing the concentration of atmospheric CO_2. The figure clearly illustrates how a once-closed system is now being overloaded, reinforcing the need to enhance carbon removal through biological processes and storage in biogenic reservoirs such as forests. Given the cumulative nature of carbon emissions and the persistence of CO_2 in the atmosphere, enhancing and protecting biogenic carbon reservoirs, such as forests, is essential. Even if fossil fuel emissions were halted today, the excess carbon already introduced into the fast cycle would remain in circulation for centuries [67].

Moreover, the challenge is intensified by projections that indicate a continued and accelerating increase in atmospheric CO_2 levels, even under current policy trajectories. Over the past 80 years, more than 100 ppm of CO_2 has been added to the atmosphere. If no substantial emission reductions are implemented, this amount could double by 2100, potentially reaching 600 ppm in optimistic scenarios and exceeding 1100 ppm under worst case scenario [71].

These projections underscore the critical role of biogenic carbon reservoirs, particularly forests, in counterbalancing anthropogenic emissions and stabilizing global climate dynamics. Forests not only serve as natural buffers against ongoing emissions but also represent a crucial mechanism for mitigating the excess atmospheric carbon already accumulated due to past human activities, acting as long-term carbon sinks and strategic assets

in the path toward carbon neutrality, particularly when integrated with negative emissions technologies such as bioenergy with Carbon Capture and Storage [72].

Central to this dynamic is the concept of biogenic carbon, which refers to the fraction of carbon contained in biological materials such as plants, animals, soils, and organic waste [73]. This naturally occurring carbon flows through the fast carbon cycle and can be actively stored in natural reservoirs like forests.

To evaluate the real contribution of these ecosystems, particularly in the Portuguese context, it is essential to quantify the amount of biogenic carbon stored in forest biomass.

5.2. Quantification of Carbon Stored in the Portuguese Forest

Carbon is the primary constituent of biomass, with its quantity varying depending on its specific type [74]. This element can be easily determined through elemental analysis, which quantifies the mass fraction of the constituent chemical elements [75].

Generally, biomass has a carbon content that ranges from 35 to 65% of its dry weight [76]. For estimates of the amount of carbon stored in forests, a carbon content of 50% is commonly used as standard [76–79].

Thus, the amount of carbon stored in forests can be estimated by combining the total available biomass with its corresponding carbon content. The accuracy of this estimate will naturally depend on the data quality regarding the biomass and the adopted carbon content.

To account for the forest's contribution in mitigating the greenhouse effect, it is common to convert the stored carbon (m_C) into CO_2 equivalent (CO_2eq) using Equation (1), which relates the molecular mass of carbon dioxide to the molecular mass of carbon [15].

$$CO_2\text{eq} = m_C \times \frac{44}{12} \quad (1)$$

In the case of the Portuguese forest, the carbon stored was calculated and expressed in terms of CO_2 equivalent based on the biomass amounts presented in Tables 1–3, as estimated from the latest National Forest Inventory. It should be noted that the National Forest Inventory does not provide species- or component-level uncertainty metrics for biomass estimates; therefore, a quantitative propagation of uncertainty into the carbon stock calculations could not be performed.

To enhance the robustness of the carbon stock estimates in this study, a species-specific approach was adopted instead of relying on the standard assumption of 50% carbon content across all biomass types. Although the 50% value is widely used in forest carbon accounting due to its simplicity and general representativeness across broad biomass categories, it does not reflect the variability in carbon composition between different species.

Accordingly, a comprehensive review of the peer-reviewed literature was conducted to compile species-specific carbon content values for the main forest species present in Portugal. For each species, both the range of carbon content values reported in the literature and the adopted value used in the present calculations are presented in Table 4. The reported ranges reflect inter-study variability, while the adopted values correspond to the representative mean applied in the carbon stock estimation.

For the categories "other hardwoods" and "other resinous", due to the lack of specific data, a typical carbon content value of 50% was assumed, in line with standard practice in forest carbon accounting. These categories represent a relatively small fraction of the total forest biomass and carbon stock at the national scale; therefore, a moderate variation in the adopted carbon fraction would result in only marginal changes in total national CO_2-equivalent estimates.

Table 4. Species-specific carbon content of forest species (% dry basis, m/m).

Species	Carbon Content Range [%]	Adopted Carbon Content [%]	Reference
Maritime pine	49.30–50.21	49.76	[80,81]
Eucalyptus	47.30–48.20	48.20	[80,81]
Cork oak	49.23–51.61	50.42	[82,83]
Holm oak	46.50–47.70	47.10	[81,84]
Oaks	47.20	47.20	[81,85]
Stone pine	48.10–51.50	49.80	[81,86]
Chestnut tree	46.50–47.10	46.80	[81,85]
Carob tree	44.02–45.92	44.97	[87,88]
Acacias	47.00–48.20	47.60	[80,89]

The species-specific carbon content values described above were applied to the biomass data presented in the previous sections to derive more realistic estimates of biogenic carbon storage in Portuguese forests. Due to the lack of consistent, species-specific carbon content data for individual biomass components (wood, bark, leaves, branches, and roots), the species-specific carbon contents reported in Table 4 were uniformly applied to all tree components when estimating component-level carbon stocks. The results of this calculation are summarized in the following tables.

Table 5 presents the amount of carbon stored in live biomass across different forest species, distinguishing between trees and undergrowth. The values are expressed in kilotonnes of CO_2 equivalent (kt CO_2e). Tables 6 and 7 provide a more detailed breakdown: Table 6 quantifies the carbon content in individual tree components (wood, bark, leaves, branches and roots), while Table 7 focuses on carbon stored in dead biomass, including standing and fallen trees, stumps and leaves. These tables support the assessment of carbon storage distribution within Portuguese forests, offering insight into the relative contribution of each biomass fraction.

Table 5. Carbon stored in live biomass in the Portuguese forest.

Species	Trees [kt CO_2e]	Undergrowth [kt CO_2e]
Maritime pine	82,068	7152
Eucalyptus	61,344	8147
Cork oak	63,393	5916
Holm oak	16,925	2314
Oaks	12,513	623
Stone pine	16,891	1479
Chestnut tree	13,882	257
Carob tree	1022	115
Acacias	4538	52
Other hard woods	20,680	1613
Other resinous	6673	403
Total	299,928	28,074

As expected, the living biomass, composed of trees and undergrowth, is responsible for the largest carbon storage, with most of this carbon stored in wood. Maritime pine, eucalyptus and cork oak have the largest carbon stocks, with more than 70% of the total carbon stored in trees. Maritime pine stands out with 82,068 kt CO_2e stored in the trees, followed by eucalyptus (61,344 kt CO_2e) and cork oak (63,393 kt CO_2e). Curiously, eucalyptus contributes the highest amount of carbon in undergrowth (8147 kt CO_2e), exceeding that of maritime pine (7152 kt CO_2e) and cork oak (5916 kt CO_2e), reflecting its dense regrowth and high productivity.

Table 6. Carbon stored per tree component in the Portuguese forest.

Species	Wood [kt CO_2e]	Bark [kt CO_2e]	Leaves [kt CO_2e]	Branches [kt CO_2e]	Roots [kt CO_2e]
Maritime pine	40,833	9214	4452	9816	17,753
Eucalyptus	33,244	5673	4719	5426	12,248
Cork oak	34,239	10,076	1960	9299	7783
Holm oak	4956	1675	0	3057	7253
Oaks	5330	0	519	3842	2838
Stone pine	4072	566	530	11,139	584
Chestnut tree	1922	480	583	704	10,485
Carob tree	165	0	0	445	412
Acacias	1658	314	279	471	1815
Other hard woods	9753	0	752	6087	4088
Other resinous	3263	733	385	862	1148
Total	139,436	28,732	14,178	51,147	66,708

Table 7. Carbon stored in dead biomass in the Portuguese forest.

Species	Standing Trees [kt CO_2e]	Fallen Trees [kt CO_2e]	Stumps [kt CO_2e]	Leaves [kt CO_2e]	Total [kt CO_2e]
Maritime pine	1679	365	203	44	2290
Eucalyptus	583	389	269	48	1288
Cork oak	721	129	20	9	880
Holm oak	276	35	2	2	314
Oaks	87	0	14	5	106
Stone pine	73	37	9	7	126
Chestnut tree	1441	0	3	2	1447
Carob tree	0	0	0	0	0
Acacias	175	0	2	0	176
Other hard woods	128	275	35	13	451
Other resinous	55	18	7	2	83

To evaluate the robustness of the adopted species-specific carbon fractions, carbon stocks for trees and undergrowth were also estimated using the conventional assumption of a uniform 50% carbon content. The comparison reveals systematic, species-dependent deviations. While differences are negligible for some species (e.g., maritime pine and stone pine), they reach approximately −6% for chestnut and exceed −10% for carob tree. These results demonstrate that the use of a fixed carbon fraction introduces non-uniform bias into species-level and national carbon stock estimates, particularly in heterogeneous forest systems.

When analyzing the carbon distribution across tree components (Table 6), wood clearly dominates, representing approximately 46.4% of the total live biomass carbon (139, 436 out of 300,201 kt CO_2e). However, roots and branches together represent over 39.3%, indicating the importance of accounting for below-ground and structural biomass when estimating forest carbon stocks. The remaining carbon is distributed among bark (9.6%), and leaves (4.7%). Notably, stone pine stores more carbon in branches than wood, which is unusual among the listed species and may relate to its canopy architecture.

Dead biomass contributes to carbon storage, as indicated in Table 7, although the amount is considerably lower than living biomass, with a total of 7160 kt CO_2e across all species. Dead biomass contributes to carbon storage to a much lesser extent than living biomass, totaling 7160 kt CO_2e across all species (Table 7). Maritime pine accounts for the largest share of dead biomass carbon (2290 kt CO_2e), likely reflecting its wide distribution and higher susceptibility to wildfires and biotic disturbances. Overall, carbon storage is dominated by living biomass, particularly the wood component, highlighting

the importance of maintaining healthy and mature forest ecosystems for effective carbon sequestration. Although dead biomass represents a smaller carbon pool, it gradually releases biogenic carbon through decomposition and can also serve as a resource for bioenergy when sustainably managed. These results emphasize the role of strategic forest management in both enhancing carbon sequestration and reducing wildfire risk through the controlled removal and utilization of forest residues.

6. Global Research Trends on Forest-Based Biogenic Carbon

6.1. Data Sources and Scope

To contextualize the present study within the broader scientific landscape, a concise and exploratory bibliometric screening was conducted using the Scopus and Web of Science (WoS) databases. Query-based searches targeting carbon, biogenic carbon, and biogenic carbon from forest biomass were performed for the period 2000–2024.

In both databases, keyword-based search strategies were applied to progressively narrow the scope from general carbon research to biogenic carbon and, finally, to forest-based biogenic carbon. The corresponding queries and the number of publications obtained for each topic are presented in Tables 8–10.

Due to the broad scope of the term "carbon", searches were limited to article titles and keywords to avoid the inclusion of studies in which the term is used only in a general or contextual manner.

The biogenic carbon search strategy incorporated commonly used terms in the literature, including "bio", "renewable", and "green", to capture variations in terminology describing carbon of biological origin. Although "green" can be broader than forest-derived carbon, it is frequently used to refer to carbon captured through photosynthetic processes in biomass and was therefore retained. For the forest-based query, this terminology was maintained for consistency, while additional forest-specific terms ("forest" and "forestry") were introduced to improve thematic precision.

Table 8. Search queries and corresponding number of scientific publications on carbon-related research obtained from Scopus and Web of Science.

Database	Query	# of Publications
Scopus	TITLE ("carbon" OR "CO_2") AND KEY ("carbon" OR "CO_2") AND PUBYEAR > 1999 AND PUBYEAR < 2025	673,951
WoS	TI = ("carbon" OR "CO_2") AND AK = ("carbon" OR "CO_2") AND PY = (2000–2024)	351,230

Table 9. Search queries and corresponding number of publications on biogenic carbon obtained from Scopus and Web of Science.

Database	Query	# of Publications
Scopus	TITLE ("carbon" OR "CO_2") AND KEY ("carbon" OR "CO_2") AND TITLE ("biogenic" OR "bio" OR "renewable" OR "green") AND KEY ("biogenic" OR "bio" OR "renewable" OR "biomass" OR "green") AND PUBYEAR > 1999 AND PUBYEAR < 2025	8363
WoS	TI = ("carbon" OR "CO_2") AND AK = ("carbon" OR "CO_2") AND TI = ("biogenic" OR "bio" OR "renewable" OR "green") AND AK = ("biogenic" OR "bio" OR "renewable" OR "biomass" OR "green") AND PY = (2000–2024)	4232

Table 10. Search queries and corresponding number of scientific publications on biogenic carbon from forest biomass obtained from Scopus and Web of Science.

Database	Query	# of Publications
Scopus	(TITLE ("carbon" OR "CO_2") AND KEY ("carbon" OR "CO_2")) AND (TITLE ("biogenic" OR "bio" OR "renewable" OR "biomass" OR "green") AND KEY ("biogenic" OR "bio" OR "renewable" OR "biomass" OR "green")) AND (TITLE ("forest" OR "forestry") OR KEY ("forest" OR "forestry")) AND PUBYEAR > 1999 AND PUBYEAR < 2025	1381
WoS	TI = ("carbon" OR "CO_2") AND AK = ("carbon" OR "CO_2") AND TI = ("biogenic" OR "bio" OR "renewable" OR "biomass" OR "green") AND AK = ("biogenic" OR "bio" OR "renewable" OR "biomass" OR "green") AND (TI = (" forest" OR "forestry") OR AK = ("forest" OR "forestry")) AND PY = (2000–2024)	326

After completing the searches, results from both databases were merged and duplicates were removed using the Bibliometrix package in RStudio software (R version 4.4.1) [90]. This procedure was not applied to the general carbon category due to export limitations of the Web of Science platform, which restrict large-scale data retrieval. Consequently, only Scopus records were considered for this dataset. Although this choice may introduce some sampling bias, Scopus provides broad coverage of the topic. As the bibliometric screening is intended to characterize general publication trends rather than derive absolute publication counts, the resulting dataset is considered representative. The final number of publications for each topic is presented in Table 11.

Table 11. Final number of publications per research topic after database merging and duplicate removal, based on Scopus and Web of Science searches.

Search	# of Publications
Carbon	673,951
Biogenic carbon	8570
Biogenic carbon from forest biomass	1396

As expected, the general search on carbon yielded the highest number of publications, highlighting its extensive coverage across multiple scientific disciplines. In contrast, the most specific query, focused on biogenic carbon from forest biomass, returned the fewest publications. This outcome illustrates the increasing level of thematic specificity applied throughout the analysis and validates the bibliometric methodology adopted for progressively refining the research focus.

6.2. Publication Trends

To structure the analysis clearly, the results are presented in two complementary parts. First, a macro-level assessment of publication trends over the last 25 years is provided for general carbon research, biogenic carbon, and forest-based biogenic carbon. Second, a more focused overview addresses recent research orientations within forest-based biogenic carbon.

6.2.1. Temporal Evolution of Scientific Output

The annual distribution of publications from 2000 to 2024 was analyzed to evaluate the research trends in the three selected topics, providing a comprehensive overview of

growth in each field. The distribution related to "general" carbon research is illustrated in Figure 6.

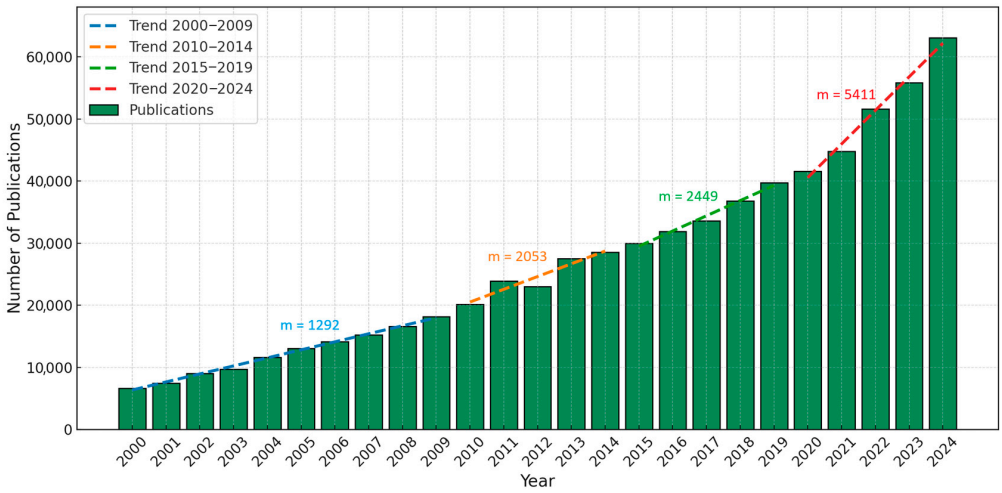


Figure 6. Number of publications related to "general" carbon from 2000 to 2024 with trend lines.

The results reveal a substantial growth in scientific production in this area, with the number of publications increasing from 6681 in 2000 to approximately 65,000 in 2024. To analyze in greater detail the variation in the number of publications over the years, trend lines were drawn for four analytical periods: 2000–2009, 2010–2014, 2015–2019 and, 2020–2024. In each case, only the slope of the regression line was considered, as the intercept is not meaningful for this type of temporal analysis. The slope was therefore interpreted as the annual growth rate, providing a quantitative measure of the increase in publications within each period.

During 2000–2009, publication growth was steady but moderate (1292 publications per year). This trend intensified in 2010–2014, reaching 2053 publications per year, reflecting increasing scientific attention to carbon-related issues. Growth continued between 2015 and 2019 (2449 publications per year), coinciding with the adoption of international climate targets such as the 2015 Paris Agreement, although without an immediate structural change in publication dynamics. The most pronounced increase occurred in 2020–2024, with an annual growth rate of 5411 publications. This acceleration reflects strengthened global climate commitments, the urgency of carbon neutrality targets for 2050, and rapid advances in carbon capture, utilization, and storage (CCUS), supported by expanded funding and policy frameworks.

Against this backdrop of rapidly expanding carbon-related research, increasing attention has been directed toward biogenic carbon, in line with its role in the natural carbon cycle discussed earlier. Figure 7 illustrates the evolution of scientific publications on biogenic carbon between 2000 and 2024.

As shown in Figure 7, publication output increased from only 12 studies in 2000 to approximately 1937 in 2024, following a clear and accelerating upward trend. Early research activity remained limited during 2000–2009 (6 publications per year), reflecting the emerging nature of the field. Growth became more pronounced after 2010 and accelerated further between 2015 and 2019 (50 publications per year), coinciding with growing policy and scientific focus on carbon neutrality.

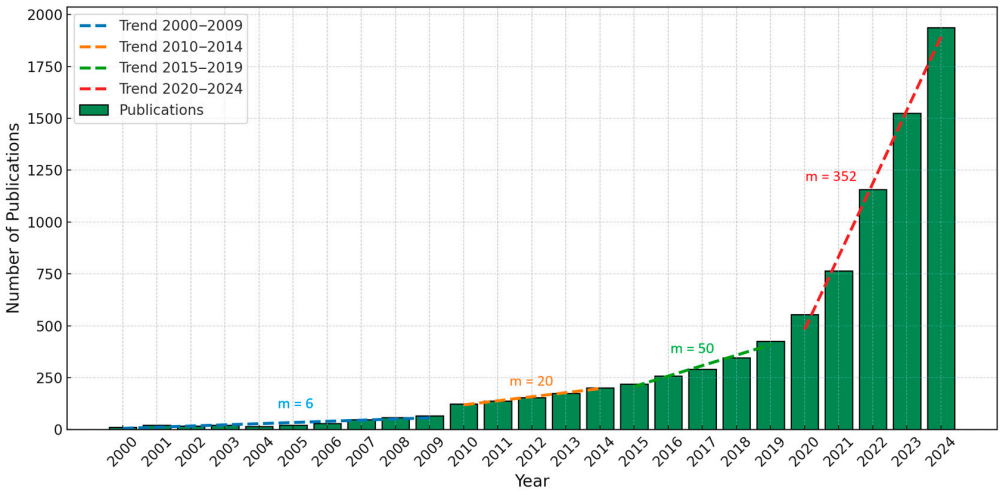


Figure 7. Number of publications related to biogenic carbon from 2000 to 2024 with trend lines.

The most substantial increase occurred in the 2020–2024 period, with an annual growth rate of 352 publications, during which research output more than tripled. This sharp rise reflects the increasing recognition of biogenic carbon as a key component of sustainable energy systems and climate change mitigation strategies. Overall, these trends indicate a clear transition of biogenic carbon from a niche topic to a well-established and rapidly expanding research field.

Based on the principles of the carbon cycle discussed earlier, particular attention has recently shifted toward biogenic carbon derived from forest, given its role in short-cycle carbon flows and its potential contribution to climate change mitigation strategies. In this context, the evolution of the number of publications on biogenic carbon from forest biomass between 2000 and 2024 is presented in Figure 8.

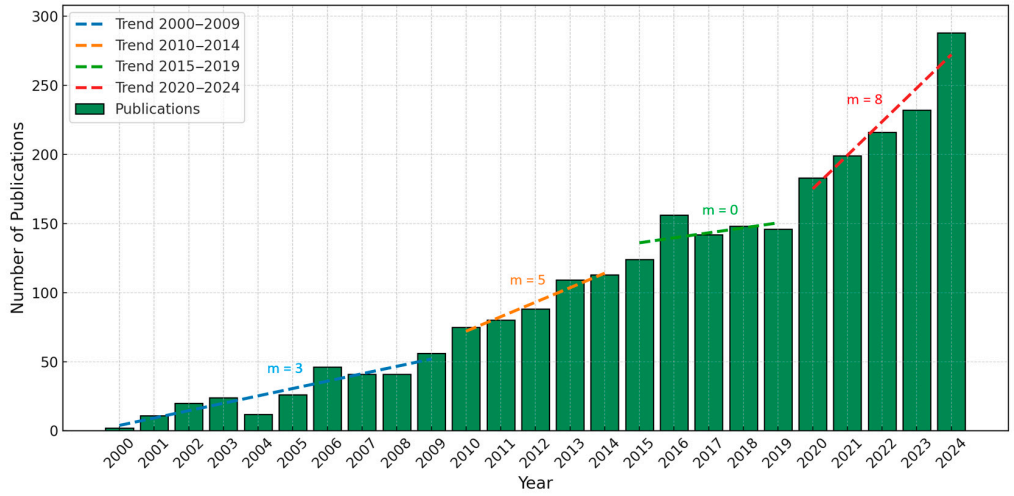


Figure 8. Number of publications related to biogenic carbon from forest biomass from 2000 to 2024 with trend lines.

As shown in Figure 8, publication output increased from only 2 studies in 2000 to 121 in 2024, following an overall upward trend. Research activity remained limited during 2000–2009 (3 publications per year) and increased modestly in 2010–2014 (5 publications per year). In contrast, the 2015–2019 period is characterized by a near-zero growth rate (m = 0), indicating a temporary stagnation, likely associated with the limited adoption of the specific terminology “biogenic carbon from forest biomass” during that period.

The most pronounced increase occurred in 2020–2024, with an annual growth rate of 8 publications, reflecting renewed scientific focus on forest-based biogenic carbon, driven by climate policies, carbon neutrality targets, and the strategic role of forest biomass in decarbonization pathways.

Although the absolute number of publications remains modest compared with broader carbon and biogenic carbon research, this evolution reflects the narrower scope of the topic rather than limited scientific interest, highlighting the increasing recognition of forest ecosystems as both carbon sinks and renewable resources.

Taken together, these results highlight the growing scientific relevance of carbon research, particularly in relation to biogenic carbon. The sustained increase in publication activity over the last decade reflects the alignment of academic research with global climate objectives and decarbonization agendas. Within this context, the emerging focus on biogenic carbon from forest biomass underscores the increasing recognition of forest ecosystems not only as carbon sinks, but also as renewable resources contributing to sustainable energy systems.

Although the absolute number of publications in this category remains lower than in broader carbon and biogenic carbon research, this outcome reflects the narrower thematic scope of forest-based biogenic carbon studies rather than a lack of scientific interest.

6.2.2. Thematic Orientation and Geographical Distribution

To further contextualize recent research activity, an exploratory bibliometric screening focused on biogenic carbon from forest sources was conducted using the Bibliometrix package in RStudio [90]. The analysis was restricted to the most recent five-year period (2020–2024) to capture current research orientations and emerging topics, avoiding earlier phases in which this research field was still incipient.

As part of this exploratory assessment, a thematic map based on centrality and density measures was generated to provide a high-level overview of the main research themes and their degree of development. The resulting thematic structure is presented in Figure 9, which summarizes the relative importance and maturity of the dominant topics addressed in recent studies on forest-based biogenic carbon.

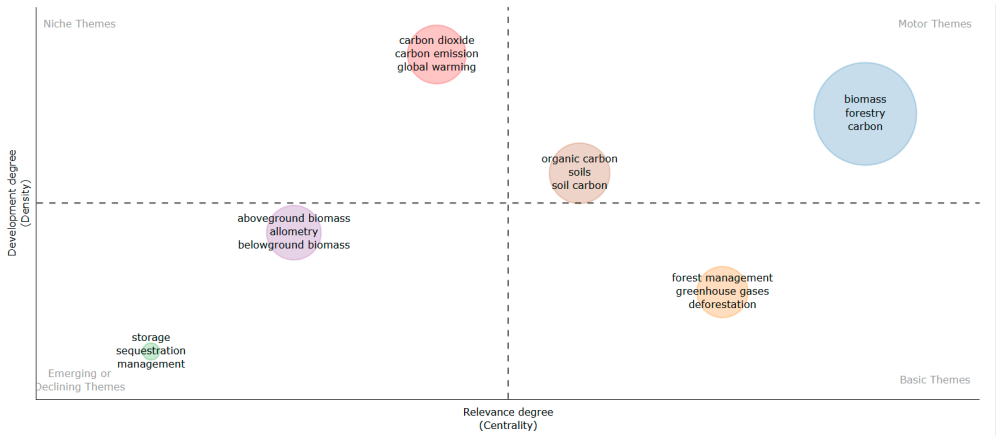


Figure 9. Thematic map on the degree of importance and development of the lines of research.

The thematic map indicates that research in this area is primarily structured around central themes related to “biomass”, “forestry”, and “carbon”, which form the core of the field. Topics associated with “carbon storage”, “sequestration”, and “forest management” appear as emerging or less consolidated themes, suggesting growing interest in forest carbon dynamics and management strategies. Additional themes related to “above-” and

"below-ground" biomass and "allometric" approaches reflect ongoing efforts to improve the quantitative understanding of forest carbon pools.

Overall, the thematic distribution suggests that research on forest-based biogenic carbon is in a consolidation phase, characterized by well-established core topics alongside a set of emerging research directions that may gain prominence as climate change mitigation and sustainable forest management continue to attract scientific and policy attention.

Following the thematic overview, it is also relevant to examine the geographical distribution of scientific production related to biogenic carbon from forest biomass. This perspective provides descriptive context on where research activity in this field is most concentrated. The distribution of publications by country, based on authors' affiliations, is presented in Figure 10.

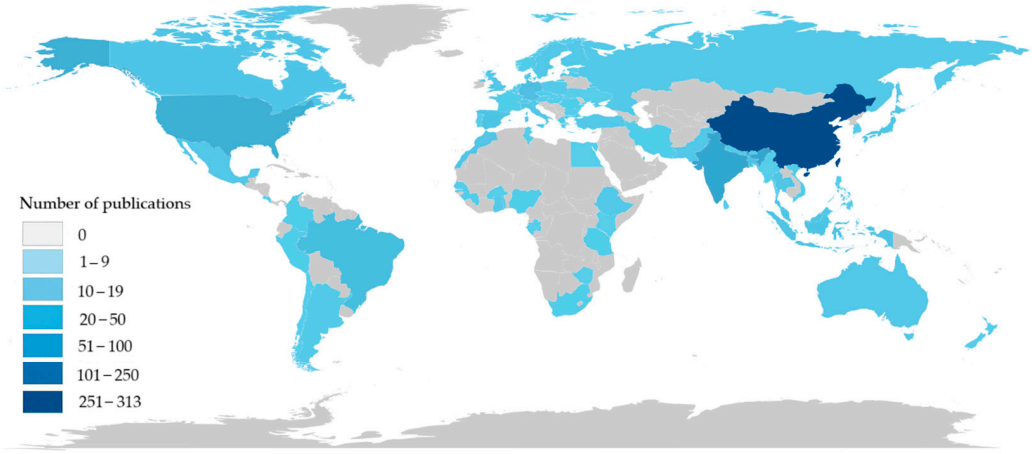


Figure 10. Scientific production of countries according to authors' affiliation in publications related to biogenic carbon from forest biomass.

The map of scientific production reveals that the main countries involved in research on biogenic carbon from forest residues are China, India and United States of America, and, to a lesser extent, Brazil and Germany. China stands out as one of the most significant contributors, indicating a strong interest and investment in this area. These results are partly driven by the concentration of forests in these countries [26], which naturally leads to a greater focus on forest-related research. To explore this relationship further, Figure 11 presents the global distribution of forest area, allowing a visual comparison between the extent of national forest resources and scientific output.

In Figure 11, the size and intensity of the green patches represent the forest area in each country: darker and larger patches indicate countries with extensive forest cover, while smaller or lighter patches correspond to more limited forested areas.

A qualitative comparison between Figures 10 and 11 suggests that several countries with large forest areas are also prominently represented in the scientific literature on forest-based biogenic carbon. This comparison is intended to provide descriptive and contextual insight into the geographical distribution of research activity and does not represent a statistical correlation or imply any causal relationship between forest area and scientific output.

Overall, this geographical overview reinforces the growing global interest in forest-based biogenic carbon as part of climate change mitigation strategies. It highlights the international dimension of research efforts in this area while underscoring the need for continued investigation, particularly in relation to sustainable forest management and the optimization of carbon sequestration and residue utilization strategies.

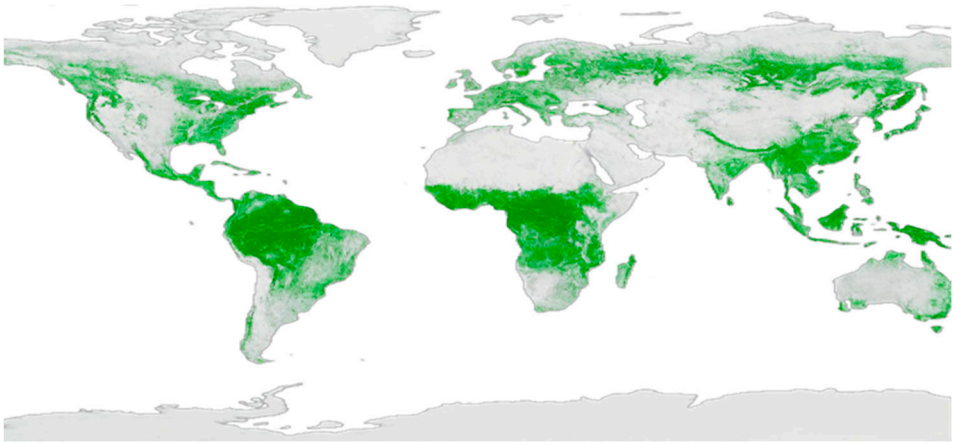


Figure 11. Global forest area distribution by country, adapted from [91].

7. Conclusions

This study confirms that Portuguese forests hold substantial potential for biogenic carbon storage, with *Pinus pinaster*, *Eucalyptus globulus*, and *Quercus suber* representing the most significant contributors. Approximately 300,000 kt CO_2e are stored in living tree biomass, with wood functioning as the dominant carbon reservoir, followed by roots and branches. This highlights the need for carbon accounting frameworks to consider both above- and below-ground components to ensure realistic national and regional estimates. Although the contribution of dead biomass is smaller (around 7160 kt CO_2e), its accumulation in unmanaged stands increases wildfire risk, reinforcing the need for active risk-reduction policies.

The main scientific contribution of this work lies in replacing the conventional uniform 50% carbon fraction with species-specific carbon contents applied to national forest inventory data. The results show that the use of a fixed carbon fraction introduces non-uniform, species-dependent biases in carbon stock estimates, particularly in heterogeneous forest systems. Adopting species-adjusted values therefore provides a more accurate and transparent basis for forest carbon accounting and reporting. The carbon estimates presented rely on the latest National Forest Inventory data available and therefore represent a snapshot corresponding to the inventory period, which may not fully capture more recent changes in forest structure or carbon stocks.

A limitation of this study concerns the application of species-specific carbon content uniformly across all tree biomass components. This assumption was adopted due to the limited availability of consistent and harmonized component-level carbon fraction data for the main Portuguese forest species. While this approach allows for a coherent national-scale assessment and represents a clear improvement over the widespread use of a fixed 50% carbon fraction, it may mask intra-tree variability in carbon content. Future research would benefit from the development of component-specific carbon datasets, enabling more refined forest carbon stock estimates and reduced uncertainty in national carbon accounting.

The bibliometric analysis indicates a clear increase in scientific publications on forest-based biogenic carbon since 2020, reflecting a growing international research focus on the role of forest ecosystems in climate change mitigation. This trend, evidenced by the temporal evolution of publication outputs identified in the bibliometric results, highlights the increasing relevance of forest biomass as a biogenic carbon reservoir within the scientific community. In this context, the Portuguese case aligns with prevailing global research directions, reinforcing the relevance of national-scale assessments of forest carbon stocks. These findings support the interpretation of Portuguese forests not only as significant

carbon sinks but also as an increasingly important research domain within international decarbonization and forest management studies.

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