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Assessing Carbon Sequestration Potential in Chestnut Coppices Using the CO2Fix Model

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Abstract

Through effective forest management, chestnut coppices (Castanea sativa Mill.) can play a crucial role in carbon sequestration, offering a sustainable approach to mitigate climate change. This study focuses on assessing the carbon sequestration potential of chestnut coppices in northeastern Portugal using the CO2FIX model, a tool designed to estimate carbon dynamics in forest ecosystems. Data from a field trial of chestnut coppices, located in an area known as Cimas de Mogadouro, Castelo Branco Parish, Mogadouro Municipality, where different densities of shoots per stump were tested, were used to calibrate and validate the model. The research objectives included developing parameters to calibrate the CO2FIX model, aiming for more accurate predictions of biomass and carbon stock in chestnut coppices, as well as evaluating the model estimates against observed data to refine silvicultural management practices to promote biomass growth, carbon sequestration capacity, and the sustainability of coppice systems. The results indicated that higher shoot densities, particularly in the three-shoots (T2) and five-shoots (T3) treatments, led to notable increases in biomass production and carbon storage compared to lower shoot densities. Both T2 and T3 exhibited strong values in terms of biomass and carbon accumulation; however, T2 proved to be more effective, showing greater gains in total volume and Current Annual Increment (CAI) over time. The trunk was identified as the main component of biomass and, consequently, of carbon storage across all treatments evaluated, underscoring its importance in managing carbon dynamics. These findings provide valuable insights for improving silvicultural management strategies aimed at optimizing carbon storage in chestnut coppices. Additionally, they underscore the role of effective silvicultural interventions in enhancing ecosystem services, contributing to the broader goals of climate change mitigation and sustainable resource use. Overall, this study highlights how targeted forest management practices can effectively increase carbon sequestration in chestnut coppices. Through this work, it was possible to simulate total biomass production and its components, as well as the corresponding carbon sequestration, for 42-year rotations in chestnut coppices.

Key-words: *Castanea sativa* Mill.; carbon stock; biomass; sustainable forest management

Resumo

As talhadias de castanheiro (Castanea sativa Mill.) têm um papel importante na captura de carbono, apresentando uma abordagem sustentável para combater as alterações climáticas. Neste estudo, analisámos o potencial de sequestro de carbono destas talhadias no nordeste de Portugal. Para isso, utilizámos o modelo CO2FIX, que é uma ferramenta útil para estimar como o carbono se comporta nos ecossistemas florestais. Baseámo-nos em dados de um ensaio de campo realizado numa talhadia de castanheiro em Cimas de Mogadouro, na Freguesia de Castelo Branco, Mogadouro, onde foram testadas diferentes densidades de varas por touça. Este estudo teve por objetivo a obtenção de parâmetros para calibração do modelo CO2FIX, visando obter predições mais precisas sobre a biomassa e o stock de carbono nas talhadias. Por outro lado, validar as estimativas do modelo comparando-as com os dados obtidos no ensaio, para assim analisarmos e otimizarmos as práticas de gestão florestal que promovem o crescimento da biomassa, a capacidade de sequestro de carbono e a sustentabilidade das talhadias. Os resultados mostraram que densidades mais elevadas de varas por touça, especialmente com três (T2) e cinco varas (T3), conduziram a um aumento notável da produção de biomassa e do armazenamento de carbono, quando comparadas com densidades mais baixas. Ambos os tratamentos T2 e T3 apresentaram valores expressivos em biomassa e carbono; no entanto, o tratamento T2 foi mais eficaz, com maiores ganhos em volume total e Acréscimo Corrente Anual (ICA) ao longo do tempo. A componente lenhosa do tronco foi identificada como o principal componente da biomassa e, consequentemente, do armazenamento de carbono em todos os tratamentos avaliados, sublinhando a sua importância na gestão das dinâmicas de carbono. Esses resultados fornecem informações valiosas para melhorar as estratégias de gestão silvícola com vista à otimização do armazenamento de carbono nas talhadias de castanheiro. Por outro lado, salientam o papel da silvicultura na melhoria dos serviços ecossistémicos, contribuindo para os objetivos mais amplos de mitigação das alterações climáticas e uso sustentável dos recursos. De um modo geral, este trabalho demonstrou como as práticas de gestão florestal orientadas podem aumentar de forma eficaz o sequestro de carbono em talhadias de castanheiro. Através deste estudo, foi possível simular a produção de biomassa total e por componentes, assim como o respetivo sequestro de carbono, para rotações de 42 anos em talhadias de castanheiro.

Palavras-Chave: *Castanea sativa* Mill.; stock de carbono; biomass; gestão florestal sustentável

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C. sativa: *Castanea sativa*

GHG emissions: Greenhouse Gas emissions

CAI: Current Annual Increment (m3/ha/year)

CV: Coefficient of Variation

DBH: Diameter at Breast Height (cm)

D0.30: Diameter at 30 cm height (cm)

d: Diameter (m)

dg: Mean quadratic diameter (cm)

G: Basal Area of the stand (m^2/ha)

hg: Mean height (m)

hdom: Dominant height (m)

Vcrown: Crown volume (m3/ha)

V0.30: Volume at 30 cm height (m3/ha)

Vtotal: Total Volume (m3/ha)

I. Introduction

One of the most important balances in nature is that of carbon, which determines the flow of organic matter and also governs that of other bioelements (Lancho & González, 2004). Since the Industrial Revolution, energy-driven consumption of fossil fuels has led to a rapid increase in CO2 emissions, disrupting the global carbon cycle and leading to a planetary warming impact (Piao et al., 2009). The importance of the C cycle has grown recently, primarily in relation to the issue of preventing climate change and global warming.

Global warming and the changing climate have a range of potential ecological impacts, including extreme weather events (such as floods, droughts, storms, and heat waves) (Ritchie & Roser, 2017). This situation highlights the necessity for accurate estimation of the amounts of organic carbon that can be sequestered by vegetation and soil. Quantifying the carbon balance of global ecosystems is essential not only to assess the magnitude of global sinks but to define new objectives for the management of ecosystems in the context of the global impetus to slow the rate of CO_2 growth (Piao et al., 2009).

In Portugal, similarly to trends observed in EU data, greenhouse gases (GHG) emissions began to decrease in 2005 and have continued to do so since, with the exception of 2017. The most recent data from 2022 reported by INE (2024), indicate emissions of 50, 329. 6 kt CO2eq showing an increase compared to 2021, which had emissions of 50, 096. 2 kt CO2eq.

Increases in atmospheric CO_2 can lead to increases in terrestrial carbon storage, namely through photosynthesis, land-use changes, vegetation and soil responses to continuous warming, and changes in the water cycle (IPCC, 2021). Terrestrial ecological systems, in which carbon is retained in live biomass, decomposing organic matter, and soil, play an important role in the global carbon cycle (IPCC, 2000). Increasing carbon sequestration supports several United Nations Sustainable Development Goals (SDGs), directly contributing to SDG 2 “End Hunger”, SDG 13 “Combat Climate Change”, and SDG 15 “Terrestrial Ecosystems and Biodiversity” (Rodrigues et al., 2023).

The sweet chestnut (*Castanea sativa* Mill.) is a perfect species for addressing these challenges (Cavallini & Lombardo, 2024). Its plantations provide essential ecosystem services by removing CO_2 from the atmosphere and storing carbon in soil and vegetation both in forest and agroforestry systems (Luchese et al., 2023; Patrício et al., 2024). Today chestnut groves are one of the most common forest ecosystems and landscapes in Europe (Pasquale et al., 2010), they are distributed in over 25 European countries (Manthos & Botu, 2013). In Portugal,

according to the National Forest Inventory (ICNF, 2015), chestnut occupies an area exceeding 48,000 hectares (ha), encompassing both orchards and forest woodlands (high forest and coppice). It is estimated that at least 10 percent of this area is occupied by coppices (Patrício 1996; Monteiro & Patrício 1996; Patrício et al., 2020). Although the species can be found throughout Portugal, it is most widely distributed in the northern and central mountainous areas of the country. It can also be found in the mountains of São Mamede (northern Alentejo province) and Serra de Monchique in the northern Algarve, Portugal's southernmost province (Patrício et al., 2014).

Today, significant areas of healthy coppices are left unmanaged or are managed without technical or economic intent, and they are sometimes abandoned because the market shows no preference for chestnut stems with smaller diameters (Patrício et al., 2020). According to the authors, bioenergy could be a solution for small-sized material from coppices, but the low prices paid to producers do not encourage its use. However, when wood production is combined with non-wood forest products (provisioning services) and other ecosystem services, such as regulating and supporting services, timber production can turn into a profitable investment for forest owners in mountainous regions (Patrício et al., 2022). In this regard, payments for ecosystem services, particularly for carbon, could offer a new source of income for land management. This approach could play a vital role in revitalizing numerous abandoned or poorly managed chestnut areas (Patrício et al., 2024) while also aiding in the reduction of GHG emissions.

To address these issues, this thesis aims to estimate the carbon sequestration and storage potential in chestnut coppices. Existing databases from a field trial, located in *Cimas de Mogadouro - Trás-os-Montes*, testing different densities of shoots per stool will be utilized to calibrate and validate the CO2FIX model, a software tool designed for estimating carbon sequestration and storage potential in these ecosystems. This model will allow for the quantification of carbon stock across various compartments, including above and below-ground biomass, soil organic matter, enabling simulations of results over multiple years.

The specific objectives of this study are:

- Develop a comprehensive set of parameters to calibrate the CO2Fix model, aiming to accurately predict biomass production and carbon stock in chestnut coppices subjected to different management practices in the northeast region of Portugal.
- Evaluate the accuracy of projections generated by the CO2Fix model by analyzing the agreement between predictions and observed data.

- Refine the understanding of specific parameterization processes for chestnut coppice management, aiming to optimize the precision and reliability of the model.
- Investigate limitations influencing growth rates in volume, biomass and carbon storage of chestnut coppice, aiming to provide relevant insights to optimize the sustainable management of these forest areas.

II. Bibliographic review

A. The European chestnut (*Castanea sativa* Mill.)

"One learns that…

there is only one species of genus Castanea in Europe and several around the world; even the most beautiful tree is not immortal; it is not as frugal as one might think if it is to produce quality wood for humans; its health depends on its living conditions; and we have good reasons to hope for the improvement of its descendants" (Bourgeois et al., 2004).

1. Overview

According to Bellini & Nin, (2009), different scholars believe that the origin of the word "*Castanea*" is derived from:

- Kastanis, a town of the antique Turkish region of Ponto, located on the Black Sea;
- Kastanie, a village in the region of Thessaly in Greece;
- kashtah a Persian term which also means "dry fruit".

The Chestnut tree has several other names such as: Tree of life, Tree of bread, Bread and accompaniment, The large tree, The king of the mountain, The majestic tree, The monument of nature, The great Patriarch.

The Sweet chestnut or European chestnut (*Castanea sativa* Mill.) is one of the most important tree nuts in the world (Ertan et al., 2015). It belongs to the family Fagaceae, which includes other important timber producing genera such as *Quercus* and *Fagus* (Pereira-Lorenzo et al., 2012). Evolved nearly 60 million years ago and have provided ecological services and fulfilled human resource needs within a diversity of forest ecosystems and civilizations on three continents for millennia (Clark et al., 2023).

Sweet chestnut is probably one of the tree species most associated with humans in Europe (Conedera et al., 2004a). It is cultivated both as an orchard tree for fruit production and for timber in coppice or high forest systems, providing numerous complementary products (e.g., honey, litter, mushrooms) and other ecosystem services (e.g., forest protection against natural hazards, carbon sequestration) (Conedera & Krebs, 2008).

The chestnut was important for the survival of traditional communities for centuries, before the introduction, development and expansion of potato and cereal crops (Ribeiro et al., 2020). According to the Food and Agriculture Organization (FAO, 2000) Statistical Database, the worldwide nut production is around 2.35 million metric tons annually (Massantini et al., 2021). The tree was thus planted in hard-to-reach regions with acidic and poor soils, providing sustenance where cereal cultivation was limited. This gave rise to the true "bread tree" (Bourgeois et al., 2004).

Since ancient times, chestnuts have been pivotal to the economies of many societies. Cultivated and managed as a monoculture for various purposes in several Southern and some Central European countries, this extensive use of chestnut trees led to the development of what is known as the "chestnut civilization", it shaped not just agriculture but the daily lives and social structures of communities (Clark et al., 2023).

2. Distribution

According to Pereira-Lorenzo et al. (2012), the distribution of the genus *Castanea* is divided into three geographically delimited sections with at least seven consistently recognized interfertile species:

- Asia: 4 species (*C. mollissima, C. henryi, C. seguinii, C. crenata*);
- North America: (*C. dentata, C. ozarkensis, C. pumila*);
- Europe and Turkey: (*C. sativa*).

In Europe, the sweet chestnut covers an area of more than 2.5 million hectares (Conedera et al., 2016). As stated by the author, most of the area (89%) is concentrated in just a few countries (France, Italy, followed by Spain, Portugal, and Switzerland). According to Krebs et al. (2004), the most probable natural range of the native chestnut species *C. sativa*, is delimited by six macroregions (Figure 1):

- The Transcaucasian region, north-western Anatolia;
- The hinterland of the Tyrrhenian coast from Liguria to Lazio along the Apennine range;
- The region around Lago di Monticchio (Monte Vulture) in southern Italy;
- The Cantabrian coast on the Iberian Peninsula;
- The Greek Peninsula (Peloponnese and Thessaly);
- Northeastern Italy (Colli Euganei, Monti Berici, Emilia-Romagna).

According to Conedera et al. (2004a) the distribution of sweet chestnut in Europe has been significantly shaped by human activity and cultivation practices. Originally confined to specific ecological regions, chestnut trees have been widely established across central and southern Europe, especially in mountainous areas where their cultivation became vital for local communities. This historical reliance on chestnut has led to a complex distribution pattern that extends beyond its natural range, complicating efforts to trace its original habitats. A multidisciplinary approach, based on different sources of information, incorporating pollen studies, archaeology, history and classical literature, is necessary to fully understand the evolution of chestnut distribution over time.

Genetic studies are beginning to trace its historical path. Originally from eastern Turkey and Armenia, its cultivation was spread to Western Europe by the Greeks and later the Romans (Bourgeois et al., 2004), when it played an important role in cremation rituals from the 1st century BCE to the 7th century CE (Clark et al., 2023). It is commonly believed in Portugal that the sweet chestnut, or 'castanheiro,' was introduced by the Romans. However, fossil evidence shows that the sweet chestnut was present in Portugal 8,000 years before the Roman occupation of the Iberian Peninsula, although questions remain about its survival during the glaciations (Patrício et al., 2014).

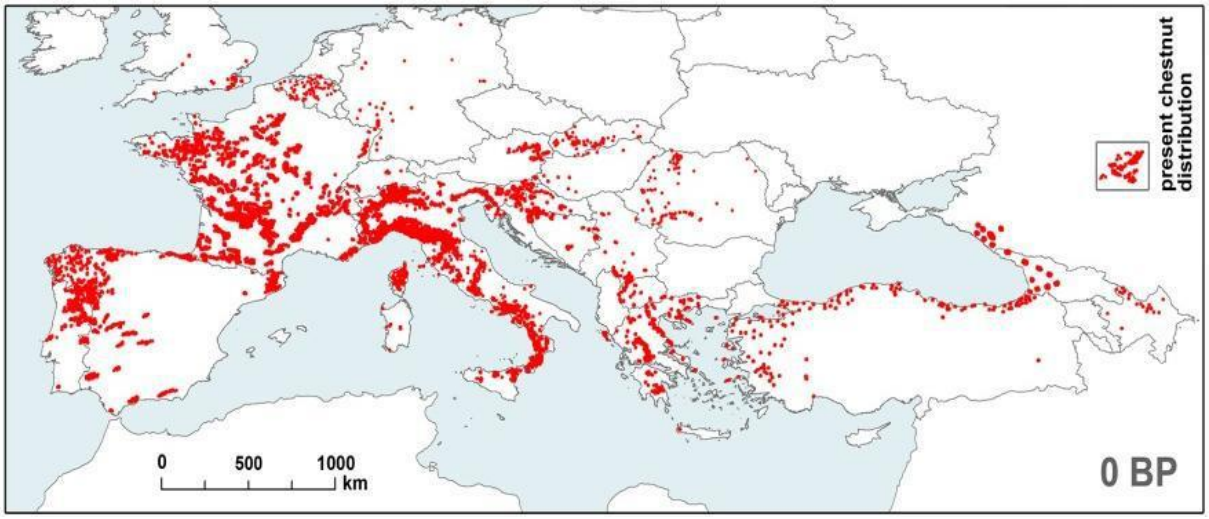


Figure 1 : Distribution of Castanea sativa in Europe (adapted from Pereira-Lorenzo et al., 2010).

3. Description

The sweet chestnut is a medium-large deciduous tree that can reach a maximum height of 30 meters; these trees have a great longevity, sometimes living for several centuries. Initially, it grows relatively quickly until around 50-60 years of age, after which its growth slows down (Conedera et al.,2016).

According to the authors the trunk bark is olive green on young shoots and then darkens; it is gray on the branches and later turns brown. The wood is yellowish-brown with a pronounced porous zone and distinct sapwood. The wood is hard, without knots when pruned, and splits easily. The leaves are alternate, deciduous, and lanceolate to oblong in shape. They are large, approximately 8-25 cm long, 5-9 cm broad. Also, the leaves are thick, glossy, dark green on the upper surface, and much lighter green on the underside. They are equipped with a long petiole (figure 2).

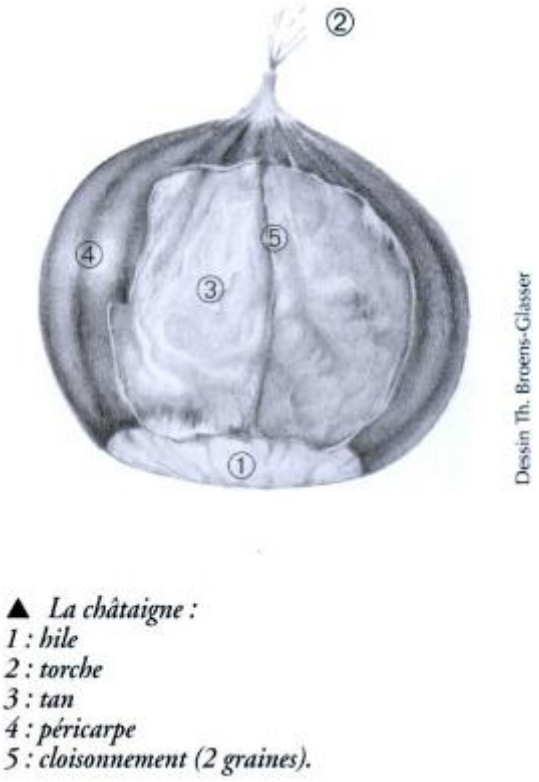
Figure 2 : Oblong-lanceolate leaves, bright green in color with toothed margins (adapted from Conedera et al., 2016).

The sweet chestnut is monoecious, bearing both male and female flowers, as illustrated in Figure 3. Male flowers are grouped in catkins measuring 5 to 15 cm in length, while female flowers are typically located at the base of the male catkins on the upper part of the current year's shoots (Conedera et al., 2016).

Figure 3 : Unisexual male and female inflorescences: long yellow catkins of male flowers clustered in bundles and composed of numerous stamens and a solitary female inflorescence comprising an ovoid cupule with styles on top (adapted from Conedera et al., 2016).

Flowers develop from late June to July and may be pollinated by wind in dry weather or by insects in wet conditions. Each flower can then produce a fruit, which may contain one or more seeds or nuts, depending on the number of fertilized ovules, as shown in Figure 4 and 5.

Figure 4 : Edible nuts of the sweet chestnut (adapted from Conedera et al., 2016).



▲ *La châtaigne :*
1 : hile
2 : torche
3 : tan
4 : péricarpe
5 : cloisonnement (2 graines).

Figure 5 : Drawing of sweet chestnut's nut (1: Hilium; 2: Torch; 3: Tan-Shell; 4: Pericarp; 5: Partitioning (2 seeds)) (adapted from Bourgeois et al., 2004).

4. Environmental and ecological factors

According to Yılmaz (2015), tree growth is primarily regulated by temperature and precipitation and, secondarily, by soil moisture. Water availability in the soil is a crucial factor influencing the growth and productivity of nuts (Mota et al., 2018).

a. Habitat and ecology

Sweet chestnut, thrives in a variety of landscapes, including plains, hills, and mid-altitude mountains. Geographical parameters, such as latitude and elevation play an important role in chestnut tree cultivation. It usually found at elevations ranging between sea level and 1800 m, depending on the latitude, although elevations between 700 and 1000 m give the best conditions for fruit production (Freitas et al., 2021).

According to Pereira et al. (2011), its cultivation is roughly within the latitude belt from the 27° N (Canary Islands, Spain) to the 53° N (south of the United Kingdom, UK), parallel. The Azores archipelago (Portugal) corresponds to the western limit (25–31° W) of the production of *Castanea sativa.*

b. Climate

Climate factors determine where the sweet chestnut can successfully grow and develop. It is well-suited to climates that are neither too hot nor too cold, typical of regions with supra-Mediterranean (just above the Mediterranean climate) and sub-Atlantic (just below the Atlantic climate) characteristics.

The species is quite adaptable to different environments, but its growth and establishment are primarily restricted by two climatic factors: cold temperatures and drought conditions. According to Freitas et al. (2021), sweet chestnut is a mesophilic species from warm temperate climates since the best conditions for its growth are moderate temperature and humidity. This explains its prevailing location in high-elevation areas in Southern Europe.

Additionally, chestnut is a moderate thermophilic species, optimally develops in regions with annual mean temperatures between 8 °C and 15 °C, and can tolerates well maximum temperatures up to 27–31 °C and endures absolute minimum temperatures of as low as –16 °C.

c. Rainfall

In Portugal, the chestnut tree requires an average annual precipitation of 800 to 1600 mm (Alves, 1988), with the species demanding that the amount of rainfall from April to July accounts for at least 25% of the total annual precipitation, which means a minimum rainfall of

200 mm (Patrício, 1996). This does not exclude the possibility of achieving very good productivity (> 13 m³/ha/year) with lower rainfall, but on relatively richer soils with good water reserves (Bourgeois et al., 2004).

d. Light

Sweet chestnut is an heliophilous species (attracted by or adapted to sunlight). According to Freitas et al. (2021), the sweet chestnut growth is affected by solar radiation, affecting both photosynthesis and morphology. It grows in average annual sunlight conditions ranging from 2400 to 2600 hours. Other studies indicate that 75% of the maximal photosynthetic rate is achieved at light levels of 900–1000 μmol $m^{-2}s^{-1}$, which corresponds to nearly half of the full sunlight intensity.

According to Bourgeois et al. (2004), seedlings need a minimum amount of light to survive, which is why they are almost never found in fully covered coppices. While they can tolerate partial shade during regeneration cuts, they grow better and faster in full light. Until the formation of the rhytidome (mature bark), the thin and smooth bark of young stems does not provide sufficient protection against sunburn. Ideally, chestnut trees should have their tops in the sun and their trunks in the shade.

e. Wind

According to Bourgeois et al. (2004), the sweet chestnut, which is supple and flexible, rarely breaks under strong winds. However, due to its shallow root system and the significant wind resistance posed by its stools, it is more prone to being uprooted. The high density of stems in an unthinned coppice, combined with the weight of these stems relative to the root system, likely increase its susceptibility to wind damage.

In terms of growth, it has been observed that stands are less vigorous in windy areas (coastal fringes, ridges, plateaus). As for the role of wind as a factor promoting canker (rolled bark disease), it is far from proven (Bourgeois et al., 2004). Wind-sheltered locations are the best option for the installation of chestnut crops (Freitas et al., 2021).

f. Soil

Soil is a fundamental element of forest ecosystems (Campagnaro et al., 2023). In Portugal, chestnut stands grow in soil types as Regosols, Cambisols and Leptosols (Patrício et al., 2009). The soil pH is crucial for the optimal growth of chestnut trees, they generally prefer deep, soft, acidic soils (pH ranging from 4 to 6.5) (Beccaro et al., 2019).

While chestnut trees can thrive in various acidic soils with a pH range of 4.5 to 6.5, optimal productivity and health occur when soil acidity is lower, around a pH of 5.5. However, other factors, such as soil water reserves and the number of rotations on the same stump for the coppices, also play a crucial role in overall productivity (Bourgeois et al., 2004).

Regardless of the parent rock type; whether granite, schist, sand, loess, clay, or flint deposits, chestnut can produce quality wood. Chestnut trees perform well in young, less developed, or even relatively shallow soils, as long as the rock is fractured. Brown mesotrophic, brown acidic, ocher, and leached soils are particularly favorable. In contrast, their growth and wood quality are generally poor in podzolic soils and soils affected by hydromorphism (Bourgeois et al., 2004). However, for quality timber production, it requires relatively good soils with more than 60 cm of depth. Additionally, sweet chestnut dislikes chalky soil, but appreciates sedimentary or siliceous soils. Their roots tend to decay in poorly drained soils, which help to explain why they prosper on hills and mountainsides (Pereira et al., 2011).

According to Bourgeois et al. (2004), the chestnut tree is classified as a calcifuge species, meaning that excessive absorption of calcium ions (Ca^{++}) can lead to chlorosis and ultimately death. This issue arises in soils containing active limestone, such as carbonate soils or calcareous soils rich in calcium ions. Therefore, chestnut trees are often found in dolomite areas (magnesium-rich rock) or on soils developed from hard limestone, where active limestone is absent. Despite their sensitivity to calcium, chestnut trees still require calcium ions for healthy growth. Certain acidic soils, particularly in Limousin, are nearly devoid of calcium, resulting in a high concentration of ionic aluminum. This mineral imbalance, characterized by a very high Al/Ca ratio, negatively impacts the productivity of chestnut coppice and contributes to wood fragility, leading to ring shake. The introduction of calcium sources, like finely ground magnesium limestone, has shown promise in improving coppice growth.

According to the authors, the mineral deficiency in the soil is reflected in the chemical composition of the wood. While mineral amendments significantly influence this composition, it's still too early to ascertain if they effectively reduce the risk of ring shake.

g. Water in the soil

Establishing a clear and direct relationship between soil and plant water status can be quite challenging, as climatic conditions also play a role. The soil-water-plant relationship is deeply dependent on plant’s physiology and morphology as well as on soil’s features (Mota et al., 2018).

According to Bourgeois et al. (2004), cultivating chestnut trees on highly permeable soils when there is a significant summer water deficit can be very difficult, if not impossible. Conversely, a very wet spring can lead to the development of ink disease or Armillaria root rot, or cause root asphyxia in poorly drained soils. In this context, the authors established a relationship between soil water content and plant water status, highlighting that the best photosynthetic rates occur when stem water potential ranges from -1.2 to -0.5 MPa. This finding underscores the necessity of monitoring soil moisture levels to maintain healthy chestnut trees.

According to the authors, excess water is a primary limiting factor, whether due to temporary or permanent waterlogging with stagnant or flowing water, provided it occurs less than 50-60 cm deep. Conversely, whether caused by insufficient depth, excessive porosity, or prolonged summer water deficit, water shortage is also a limiting factor. The soil's available water capacity should not be less than 120 mm. All this factors must be considered for a correct water management (Mota et al., 2018).

h. Texture and structure

Preferred textures include sandy loam, loamy sand, and loam. These fragile textures require optimal conditions for machine passage. Stone content can be high (30%) if the usable depth and fertility are adequate (e.g., in schist soils). Massive structures, associated with fine loamy or clay-sandy textures, cause irreversible compaction, spring sealing, and summer mass uptake, hindering root development (Bourgeois et al., 2004).

i. Depth

The depth of soil is a critical factor in the successful cultivation of chestnuts, it can compensate for chemical deficiency or low water retention capacity (Freitas et al., 2021) in orchards. The soil depth for quality timber production from coppice should be at least 60 cm.

5. Threats

Sweet chestnut is considered threatened due to its sensitivity to various diseases. The 19th century was marked by the spread of sweet chestnut major diseases, e.g. ink disease, and chestnut blight (Campagnaro et al., 2023).

a. Ink disease (*Phytophthora cinnamomi*)

According to Vannini & Vettraino (2001), ink disease is one of the most destructive diseases affecting sweet chestnut. It causes root and collar rot of adult trees and of seedlings in nurseries,

plantations and forests. Symptoms of the disease on adult trees include chlorotic leaves reduced in size, thinning of the crown, and immature husks remaining on the tree after leaf-fall.
Soil and temperature indicators, confirmed that low water soil availability; accumulation of water on clay soils and high temperatures are destabilizing factors for chestnut growth, inducing a loss of plant vigor and making the trees vulnerable to ink disease (Freitas et al., 2021). The disease is caused by the oomycetes *Phytophthora cambivora* and *Phytophthora cinnamomi*, the latter is more pathogenic at temperatures of 25°C and above and does not survive freezing conditions in the soil (Anagnostakis, 1995).

b. Chestnut blight (*Cryphonectria parasitica*)

Originally from Japan and China where it causes mild cankers on Asian chestnut trees, its introduction to North America in the early 1900's was devastating. The disease essentially wiped out 4 billion American chestnut trees (*Castanea dentata*) over 40 years (Cunnington et al., 2010), and was initially reported in Italy in 1938, gradually spread throughout Europe (Clark et al., 2023).

Known as chestnut bark cancer, Chestnut Blight is a severe chestnut disease that can be controlled with naturally occurring hypoviruses in many areas of Europe. This ascomycete fungus infects the bark and cambium of chestnut trees through wounds and induces bark cankers which can lead to dieback of the distal parts after girdling branches or the entire tree trunk (Krstin et al., 2016).

c. Oriental chestnut gall wasp (*Dryocosmus kuriphilus*)

The most recent serious threat to sweet chestnut is the *Dryocosmus kuriphilus*, the Asian chestnut gall wasp, which emerged as a pest in the mid-twentieth century and is now one of the most important global insect pests of chestnut (Avtzis et al., 2019). It is problematic for nut production, but not as much for timber production, although it can induce poor shape, which can be an issue when aiming to produce quality wood.

B. Forests of sweet chestnut (*Castanea sativa* Mill.)

In Portugal, sweet chestnuts are mostly found in inland mountain regions, covering an estimated area of over 48,000 hectares (ICNF, 2015), which includes forest woodlands and orchards. Both coppice and high-forest systems of chestnut forests have been utilized for wood production (Patrício & Nunes, 2024).

1. Stand typology: coppice, high forest & mixed stand

The silvicultural system encompasses a series of practices implemented in a forest stand to promote its regeneration. Consequently, forest production systems represent different stand models and are generally classified under specific regime or cultural forms and treatment methods (Alves, 1988). Essentially, two major systems can be identified: the forestry system and the agroforestry system. According to the FAO (2000), three basic regimes or cultural forms are recognized: the coppice, the coppice-with-standards, and the high forest.

The sweet chestnut is a multipurpose tree which can be cultivated under a high forest regime for sawtimber, in a coppice regime for poles or small roundwood, or at wider spacing when nut production is the primary goal. In coppice systems, it is generally grown in pure stands, whereas in high forest regime, it can be pure or mixed with other broadleaves species such as oak, sycamore and beech. There is considerable interest in comparing those systems as management options, particularly in contexts where multiple objectives; such as nature conservation, wood production, recreation and landscape, must be met (Mitchell, 1992).

According to Mattioli et al. (2015), the potential natural value of chestnut stands has been acknowledged by the European Community's Natura 2000 network, which has designated chestnut-dominated forests and long-established chestnut plantations with semi-natural undergrowth as crucial habitats for biodiversity conservation. Additionally, various studies have emphasized their significant ecological role in supporting a wide range of flora and fauna (Mattioli et al., 2015).

a. Coppice stands

According to the FAO (2000), coppices have been in use for a long time in tropical dry woody formations whose main extracted products is firewood. In the case of chestnut, the extensive use of coppices is justified by landowner benefits: fast growth, short rotation, and the vitality of stumps preserved by periodic clearcutting, along with resilience to stress factors like forest fires and diseases (Mattioli et al., 2015).

Historically, the management of chestnut coppices was closely tied to rural economies, but changes in land use, especially rural abandonment over the last century, have had significant repercussions on sweet chestnut stands (Clark et al., 2023). According to the authors, forest abandonment has often led to extended rotation periods, in many cases doubling the normal time, which results in an excessive density of older stools. This condition along with a high

mortality rate among stools, makes them more difficult to manage and less productive (Clark et al., 2023).

According to these authors, the changes in land use, combined with the aging of chestnut coppices, have increased structural instability, heightening risks such as wildfires and hydrogeological hazards. The authors recomment that alternatives to traditional coppice management utilizing medium to long rotations for sweet chestnut are necessary, and that the treatment of overaged coppices represents an emerging area of research that includes thinning, planting for enrichment, or regeneration harvests.

Building on this line of thought, the authors emphasize the importance of implementing specific silvicultural models that not only improve growth and stem quality but also enhance the sustainability of chestnut coppices. These interventions promote a balance between economic viability and ecological health, supporting the long-term productivity of chestnut forests.

In this regard, it is important to highlight the work of Patrício et al. (2020), that explore the impact of different silvicultural management practices on the growth and stem quality of sweet chestnut coppices. They found that the application of specific models can significantly improve both growth and wood quality. The study compared various management systems over a period of 24 years, demonstrating that silvicultural interventions, such as thinning, can enhance the yield and quality of chestnut timber. Importantly, the managed plots showed superior results in terms of sawlog quality and overall growth when compared to unmanaged coppices. This research underlines the importance of tailored management to meet market demands for chestnut timber while promoting sustainability in coppice systems.

Another aspect to consider in management is that coppices are generally considered less appealing for recreation and tourism compared to high forest stands, mainly due to their higher density and smaller stem sizes. Moreover, clearcuts in coppices, which often exceed 5 hectares for sweet chestnut, can cause significant visual and ecological impacts on the landscape, particularly with larger cuts (Menéndez-Miguélez, 2015). This concern is particularly prononced in areas where aesthetic values play a crucial role in land use and management. Additionally, the lower biodiversity observed in intensively managed coppice areas, in comparison to high forest systems, may further reduce their ecological benefits and appeal to nature enthusiasts. These factors highlight the necessity for balanced management practices that take into account both economic and recreational objectives (Menéndez-Miguélez, 2015).

b. High forest stands

The ‘high forest’ is a stand made up of trees directly grown from seed on site (FAO, 2000), or in nursery. According to Peterken (1981), the high-forest systems can be managed as follows:

- Clear-Cutting System: A stand is cleared in a single felling and replaced by an even-aged stand, usually by planting;
- Shelterwood Systems: A stand is cleared in two or more successive fellings (known as regeneration fellings). The new stand is established between the first and the last regeneration fellings, often by natural regeneration. Although stands are more or less even-aged, a two-aged structure is temporarily created during regeneration;
- Selection System: Felling and regeneration are distributed continuously throughout the forest area, unlike the other systems within which at any given time they are concentrated on particular parts of a forest. Regeneration is usually natural. Sometimes the selection system can be classified as a special form of shelterwood.

For the chestnut, the management in high forests is relativevely less common than the management in coppice and typically involves the planting of seedlings (Clark et al., 2023). However, it gains significance in mixed stands of seed natural regeneration and when the goal is to produce timber of greater diameter and quality for more valuable uses.

According to Clark et al. (2023), a high forest system is a promising alternative to the traditional coppice management of sweet chestnut. This approach is believed to be more appropriate when multiple environmental, economic, social and management issues must be taken into account. High forest systems can have similar rotation lengths to coppice systems for medium-large dimensions, while producing high-value timber. Furthermore, the authors highlight the sustainability and multifunctionality of high-forest systems. These forests, in addition to generating periodic economic benefits, contribute strongly to the provision of ecosystem services such as biodiversity conservation, carbon sequestration, soil and water preservation.

c. Mixed stands

The Portuguese National Forest Inventory (IFN), defines a stand as pure if a single tree species covers more than 75% of the area. Below this threshold, the stand is classified as mixed (even with just two species).

Socioeconomic factors and the spread of diseases have reduced interest in the management of chestnut forests. As a result, chestnut stands tend to be invaded by other species and transition into mixed deciduous forests (Silla et all., 2013).

In their study conducted in Spain, the authors found that chestnut can naturally regenerate in secondary forests without human management, but its ability to thrive depends on the age and structure of the stand. In older, chestnut-dominated stands, *sweet chestnut* remains dominant and resists competition from other species. However, in younger mixed stands, it faces high mortality due to competition with other vigorous species. The authors also suggests that forest management practices, such as a replicating gap-forming processes, could help promote chestnut regeneration and maintain its presence in mature forests.

2. Main uses of sweet chestnut

Sweet chestnut forests have been strongly favoured by humans (Campagnaro et al., 2023). It has a remarkable multipurpose character, and may be managed for timber production (coppice and high forest) as well as for fruit production (traditional orchards), including a broad range of secondary products and ecosystem services (Conedera et al., 2016), as illustrated in Figure 6.

Chestnut forests (chestnut area)			Stands with more than 50 % chestnut
	Timber production		Stands where wood production is prevalent
		Coppices	Simple coppices. Coppices with standards
		High forests	« Natural » stands. Plantations Stands converted into high forests Abandoned stands (coppices, orchards) with the structure of high forests
	Fruit production		Stands where fruit production is prevalent
		Orchards	Stands with grafted trees (groves), including row plantations for fruit production
		High forests	« Natural » stands. Plantations
	Irregular structure		Stands without a codified management
Mixed forests with chestnut			Stands with less than 50 % chestnut

Figure 6 : Definition of the chestnut forest types (adapted from Conedera et al., 2004b).

a. Non timber products

According to Conedera et al. (2016), the sweet chestnut, due to its multipurpose nature, has long been cultivated in different management systems, depending on the desired products and services.

Currently, in Europe, chestnut forests in mountainous and hilly regions play a key role in supporting low-impact tourism and are highly regarded on hunting estates, particularlly for

pheasant shoots, as they offer both cover and a food source for the birds. The aesthetic and recreational value of these landscapes, along with their contribution to biodiversity and rural economies, underscores the importance of sustainable management practices to preserve these multifaceted ecosystem services.

b. Timber products

Chestnut wood is highly valued for its versatility, natural durability, and appealing aesthetics (Braden & Russell, 2001; Patrício & Tomé, 2023; Patrício & Tomé, 2024). Known for its strength and resistance to decay, chestnut timber owes much of its durability to its high tannin content, which acts as a natural preservative. This makes it ideal for producing high-quality wood for various purposes. Historically, chestnut was also widely used for tannin extraction, a practice that was made sustainable due to the species strong resprouting capacity (Conedera et al., 2016).

Pure chestnut high forests are relatively uncommon, occupying only a small portion of chestnut forested areas, and mainly produce timber for construction, furniture, and long poles. In contrast, the coppices dominate chestnut forest management, covering approximately 80%. This regime is primarily used to produce small-diameter logs for traditional fencing stakes, paling and hop poles but also medium-large diameters in good site indexes. Other minor uses for coppiced chestnut include turnery, cask staves, walking sticks, basketry, charcoal and firewood. Historically, chestnut bark was used for tanning leather, and more recently, split coppiced chestnut has gained popularity in the production of rustic garden furniture and climbing frames for plants and children (Braden & Russell, 2001). According to the authors, chestnut timber grown in coppice systems is characterized by fast growth in the juvenile stage. The higher proportion of denser summer wood fibers in relation to the spring wood vessels enhences its strength. Optimal strength values are typically attained with five to seven annual growth rings per 25 mm. Chestnut timber sawn from logs with mid-diameters ranging from 150 to 225 mm and aged between 15 and 30 years is considered most suitable, showing minimal signs of ring shake. Additionally, in areas with high site quality, extending the coppice rotation can yield larger and higher-quality logs suitable for sawmilling, enhancing the versatility and economic value of the wood (Patrício et al., 2020; Clark et al., 2023).

3. Silvicultural management models and chestnut wood quality

Wood quality is a multifaceted concept encompassing various factors, including wood defects, anatomy, and physical and mechanical properties. Foresters have long sought easily measurable

parameters, such as cambium age, ring width, and tree age, that could serve as reliable indicators of wood quality. Wood density, in particular, influences workability, mechanical strength, and other important attributes like wood health and durability (Romagnoli et al., 2014). In order to optimize wood quality in chestnut coppices, many approaches and elements should be taken into consideration to achieve production objectives. According to Clark et al. (2023), management goals and timber quality are closely linked and depend on factors such as site productivity, stand age, and sources of regeneration (e.g., wild seed versus planting) as can be seen in Figure 7. They highlight that biomass fuels and other wood products, like vineyard poles, can be produced on marginal sites with short to medium rotations (20–30 years). In contrast, high-quality timber production requires extending rotations (40–45 years) in productive stands by selecting one shoot per stump.

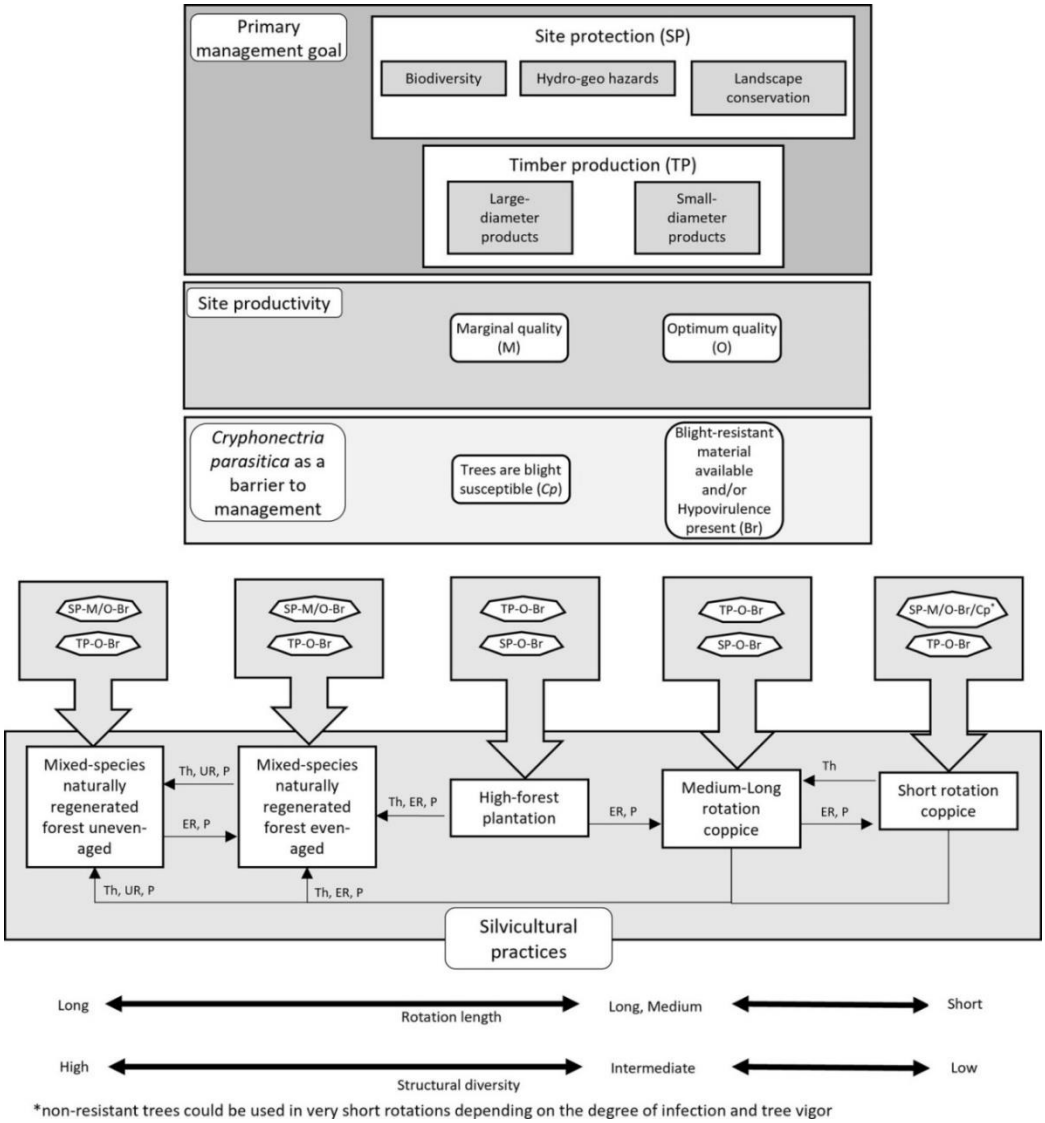


Figure 7 : Conceptual model for silvicultural practices for sweet chestnut for two primary management goals considering site and disease conditions. (adapted from Clark et al., 2023).

The management of sweet chestnut for timber production requires a comprehensive understanding of silvicultural practices that enhance growth and quality (Benedetti-Ruiz et al., 2023). The tradition of managing *Castanea* forests as coppice for timber production has been developed almost exclusively for sweet chestnut, owing to its high resprouting capacity. Dating back to Roman times, Chestnut coppices were characterized by the traditional management that we can still see today, it is based on the non-existence of thinning or other silvicultural systems, and the coppices are harvested on short rotations in order to produce construction or fencing materials (small to medium-sized poles) or firewood and charcoal for cooking, heating, and fuel (Beccaro et al., 2019).

In the following decades, new practices have been introduced to improve the production of high-quality wood, based on the lengthening of rotation periods, and the application of early and intense frequent thinning to the single tree-oriented silviculture (Beccaro et al., 2019). The table 1 illustrates a silvicultural management model developed by Bourgeois et al. (2004):

Table 1 : Silvicultural management models (adapted from Bourgeois et al., 2004.

Objectif	**Production objectives**	**Characteristics**	**Interventions**
Small wood	- Production of small logs with diameters between 17.5 and 28 cm at 1.30 m (circumference 55 to 90 cm) in 30-35 years. - valued as billets and joinery logs. - Maintain the coppice regime, well-suited for this type of production, with a traditional rotation of 30-35 years.	- The proposed silviculture is quite simple and aims to accelerate and guide the significant natural selection occurring in the coppice, focusing on mass improvement. - One hectare can support 1,500 such trees by the end of the rotation - Less retention of trees during thinning leads to a higher volume of joinery wood. - Earlier interventions can achieve the objective more quickly, sometimes before 30 years.	**Single Thinning:** - Targeted on individual trees, imperative starting at a young age. - When the coppice reaches 10 to 12 m in height (between 10 and 14 years old, with 17 years being the upper limit), a thinning is performed that removes 70 to 80% of the living trees. Despite the significant number of trees removed, it is a thinning from below, where all trees that will not yield timber in the final cut are eliminated. **Thinning + Cleanings:** The cleaning is performed when the coppice reaches 7 to 9 m in height, retaining 2,500 to 3,000 trees/ha. This results in a removal of 50 to 75% of the living trees. Five years later, thinning reduces the density to 1,500 trees/ha, allowing for product extraction.
Logs	- Production of logs with diameters > 38 cm at 1.30 m (circumference: 120 cm to 1.30 m) in 40-50 years. - Over time, the coppice will be transformed into a stand originating from seedlings.	-The strict regime of simple coppice becomes a high forest on coppice (the coppice serving to accompany a high forest on stumps). -This involves extending the rotation of the coppice cuts, performing strong thinning, and aiming for a limited number of high-quality trees for a higher final income. - The essence of silviculture lies in the designation, shaping, and pruning of future stems to have a dynamic thinning from above.	**Designation**: - Selection of future trees based on strict criteria to ensure their growth and quality. **Pruning**: - Dynamic thinning from above to relieve selected trees from the competition of the coppice, particularly at a young age.
Small logs	-Produce marketable wood in small logs and small diameter “wood for joinery” of 20 cm at the small end in 35-40 years. -The objective is to obtain trees of 28-35 cm in diameter (90 to 110 cm circumference) at 1.30 m, with a clean stem of at least 5 m, without artificial pruning, which is too costly.	- It conserves the coppice regime for at least one rotation, often extending it up to 40 years to obtain the desired products, with a final density of 400 to 800 trees/ha. - Requires vigorous, homogeneous coppices with straight trunks (growth of trees of 0.8 to 0.95 cm in diameter, 2.5 to 3 cm in circumference).	**Cleanings**: - Strong cleaning of trees before 15 years to avoid the growth of undesirable shoots. **Thinning**: -A second thinning is carried out, targeting the 100-150 most beautiful trees (pruned), with a conserved density of 400 trees/ha. **Mixed Thinning**: -Thinning from below and above with 400-800 trees/ha, aiming to maintain the largest trees. **Pruning**: -Complementary pruning of the largest trees after a strong first thinning, to obtain clean logs.

C. The potential ecosystem services offered by chestnut forests

1. Ecosystems and their services

An ecosystem is a dynamic network of plant, animal, and microorganism communities, along with the nonliving environment, all interacting as a functional unit. Humans are an integral part of ecosystems (Millennium ecosystem assessment, 2005). Ecosystems have strong internal interactions among their components and weaker interactions across their boundaries. A practical boundary for an ecosystem is often where multiple discontinuities coincide, such as in the distribution of organisms, soil types, drainage basins, or depth in a body of water. At a larger scale, ecosystems at regional and even global levels can be assessed based on shared basic structural units

As Figure 8 shows, de Groot et al. (2002) presents a way to assess ecosystem functions, goods, and services. It highlights how the complex interactions in ecosystems are simplified into key functions that provide valuable resources and benefits for people.

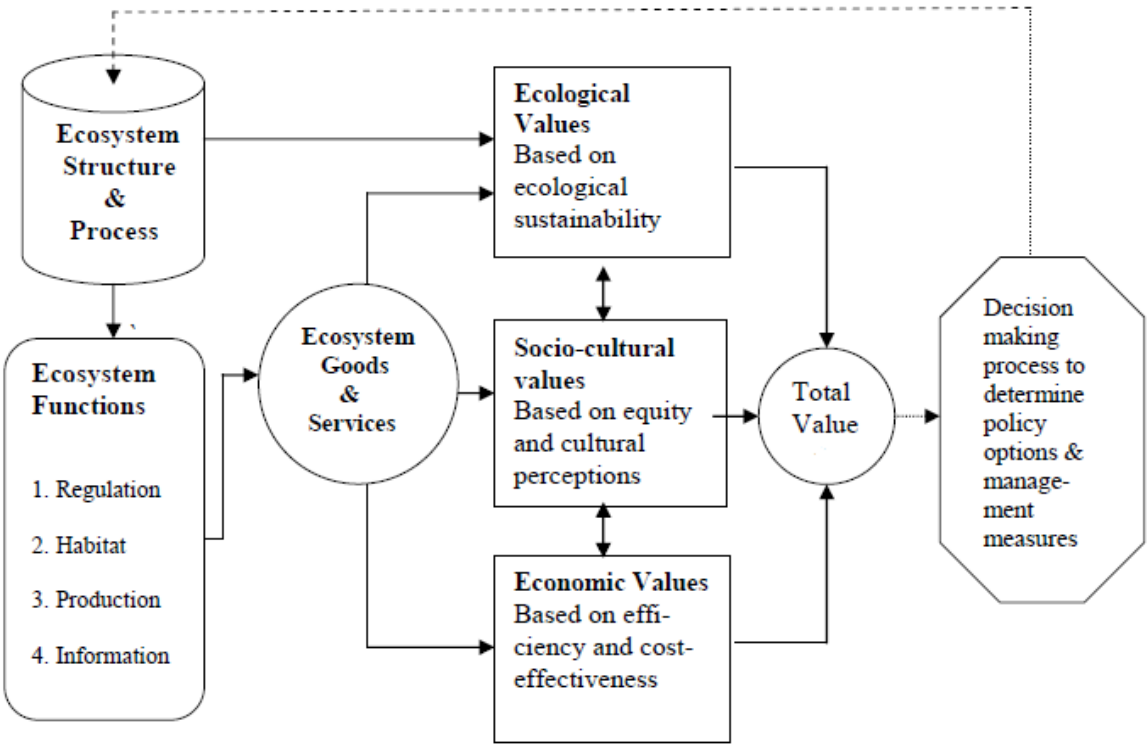


Figure 8 : Framework for integrated assessment and valuation of ecosystem (adapted from de Groot 2002).

Ecosystem services serve as the vital connections between ecosystems and human societies. These services can be divided into four main categories:

- Provisioning Services: These include the supply of food, water, and other essential resources.
- Regulating Services: Encompasses services like flood and disease control.
- Cultural Services: Provide spiritual, recreational, and cultural benefits.
- Supporting Services: Involves nutrient cycling and other processes that sustain life on Earth.

According to Luck et al. (2009), ecosystem services are defined as components and processes within ecosystems that directly enhance human well-being. These services manifest in various forms:

- Direct Consumption: Some services can be directly utilized, such as water and food.
- Experiential Benefits: Others are experienced through aesthetic appreciation, like the scenic beauty of a waterfall, a lush mountain landscape, or the sight of a monarch butterfly, which evoke feelings of awe.
- Fundamental Environmental Conditions: Ecosystem services also play a critical role in maintaining essential environmental conditions necessary for human life. This includes regulating stable climate conditions and providing protection against extreme events (Danley & Widmark, 2016).

2. Ecosystem services provided by chestnut forests

The sweet chestnut is known for consistently providing valuable services to human well-being, particularly in terms of provisioning services. Chestnuts have historically served as a vital source of raw materials and a staple in human diets. During times when bread was a costly and occasional food for lower-income populations, chestnuts helped mitigate the impact of famines, serving as a primary food source for these communities. The nut remains important to the local economy in many regions and is also a source of innovation for new, highly valued products. The nut remains important to the local economy in many regions and is also a source of innovation for new, highly valued products. Wood has also played a significant role throughout history, and to this day, the chestnut tree supports the bioeconomy to drive sustainable development.

Cultural services related to the chestnut tree are also important. These encompass the uses and traditions linked to chestnut trees and their fruit, gastronomy, natural heritage marked by numerous centuries-old trees, and the distinctive landscape.

Cultural services also include recreational use of the forest, such as running, picnicking, or nature observation. For instance, the Millenary Route in Portugal, a designated tourist route for monumental chestnut trees, offers an opportunity to observe these magnificent trees in the Montesinho Natural Park, located in the Trás-os-Montes region (Patrício et al., 2014).

The chestnut tree is considered one of the species with the greatest longevity, often living up to 400 years. “Guilhafonso” chestnut in Guarda in east central Portugal is believed to be over 500 years old (Patrício et al., 2014) and the “Castagno dei cento cavalla” or “Chestnut of the Hundred Horses” on the island of Sicily, which is named according to tradition, a hundred horses belonging to the entourage of the Queen of Aragon took shelter beneath it while traveling from Spain to Naples, is estimated to be around 3,000 years old (Gomes-Laranjo et al., 2007).

Additionally, chestnut forests offer learning opportunities like School outings and research by allowing many researchers to conduct numerous studies on this tree that will benefit humanity.

As well as serving as a source of inspiration like the famous paintings of Paul Cézanne “The Allée of Chestnut Trees at the Jas de Bouffan”.

Chestnut forests are critical to biodiversity conservation, supporting various plant, fungi and animal species. According to Roces-Díaz et al. (2018), these forests preserve multiple cultivars, which enhances genetic diversity and supports other ecosystem services like pollination and pest control. Additionally, nutrient cycling is sustained through chestnut leaf and wood decomposition, which enriches soil and promotes plant growth.

Finally, chestnuts forests play a central role in long-term climate regulation through carbon storage in soils and vegetation and the current trapping of CO_2 from the atmosphere (Roces-Diaz et al., 2018).

D. Biomass and carbon sequestration

1. Biomass production and carbon dynamics in chestnut coppices

With the increase of GHG emissions levels in the atmosphere, the biomass production and carbon sequestration play an essential role in mitigating the climate change. Chestnut coppices have the ability of absorbing atmospheric CO_2 and fixing it in woody tissues and soil (Carbone et al., 2024). Vegetation plays a crucial role in sequestering atmospheric carbon and nitrogen, returning these elements to the soil through litterfall from above-ground biomass and dead roots. This litterfall is a key component in various pedogenic processes; such as nutrient cycling, decomposition, mineralization, and respiration, that support the development of microfauna and microflora, which use the organic matter as an energy substrate.

While afforestation and reforestation are key management techniques for carbon sequestration and storage and mitigating atmospheric CO_2, the management of existing forests is essential to reduce the impacts of climate change. Developing sustainable management strategies that account for the complexity of silvicultural systems is crucial. Understanding the carbon cycle within forest dynamics is fundamental to manage the movement of carbon in forest ecosystems (Prada et al., 2016). Carbon pools encompass both aboveground and belowground biomass, which can store a significant amount of carbon as they grow. Carbon dynamics play a key role in regulating the global carbon cycle through processes such as photosynthesis, organic matter decomposition, and carbon sequestration. Soil can act as a major carbon reservoir by storing decomposed material. Similarly, harvested wood products can retain carbon for extended periods, depending on their lifespan.

According to Prada et al. (2016), management practices applied to chestnut coppices influence carbon distribution across various elements (biomass, soil, products). The variation in biomass among different stands is influenced by several factors, such as tree age, stand density, site conditions, and management techniques applied and their intensity. These factors are essential for understanding the carbon sequestration capacity of forest ecosystems. The impact of thinning on the carbon accumulated in biomass is less pronounced in stands with higher site indexes due to their increased productivity. In cases of intensive forest management with more than one thinning, carbon loss may occur (Prada et al., 2016). However, applying a single thinning can lead to a slight increase in total carbon. Additionally, extending the rotation period can enhance total carbon since growth is sustained for a longer period, which also results in long-term products with high carbon storage capacity.

2. Biomass estimation and carbon sequestration potential in chestnut coppice forests

Biomass estimation and carbon sequestration assessment are critical components for understanding the ecological impact that forest ecosystems have, and their consequences on climate change. For this purpose, various authors have developed allometric equations to predict biomass and carbon stocks for different parts of the tree. The wide range of proposed equations is based on data availability and the specific objectives of the estimation. The accuracy of these equations can be improved if additional attributes are included in the calculations.

The carbon content in above-ground and below-ground biomass can be estimated using a model called "CO2Fix", which also accounts for soil and wood products carbon through various silvicultural approaches related to thinning and rotation periods (Prada et al., 2016). The parametrization of the CO2Fix model included climate data, litterfall rates, sawmill processing data, and data on product lifespan and end-of-life scenarios. To understand biomass distribution in forest ecosystems, it is important to consider biomass estimation levels at different scales (individual tree, stump, and stand). In this context, variables such as diameter at breast height (DBH) and stump dimension have been identified as strong predictors of biomass at the individual tree level. According to several authors, the weights of the trunk, branches, leaves, and total biomass have shown a strong correlation with tree DBH for biomass estimation using regression analysis, confirming the significant relationship between these variables and tree biomass.

The CO2Fix model incorporates equations that allow for the simulation of total biomass and its components, as well as the sequestered carbon, based on the volume increments of the stand being simulated (Schelhaas et al., 2004). According to the authors, the CO2Fix model consists of six modules: biomass, soil, products, bioenergy, carbon finance and carbon accounting. To estimate the carbon stored in biomass, the biomass module uses the annual volume increment of stems, branches, leaves, roots, and also the silvicultural characteristics, natural mortality, thinning, and competition in order to stimulate treatments. The soil module focuses on describing carbon dynamics in well-drained soil and the decomposition rates of litter, which is determined by temperature and water availability. To trace carbon content from harvesting to processing into different products, the products module evaluates the percentage of each product produced (beams, poles, planks…) (Martínez-Alonso & Berdasco, 2015). The product module identifies three categories in function of wood products, uses and their possible re-use:

Long-term products like beams with a 40 years lifespan, 15 years for medium-term products such as poles and planks, as for the short-term products like firewood, 1 year lifespan (Prada et al., 2016).

3. Litterfall and nutrient cycling

Forest ecosystems production requires a high level of nutrients. However, soil nutrient deficiency and immobilization can negatively impact growth and biomass production. Perennial vegetation has several nutrient requirements, and if these are not replenished, trees will deplete the available soil reserves, thereby impeding sustainability.

According to Ranger & Colin-Belgrand (1996), the biological cycling of nutrients maintains a favorable medium for plant nutrition and can optimize the efficiency of a limited pool of available nutrients for biomass production. Chestnut trees contribute large amounts of organic matter to the soil through litterfall, tree mortality, and root decay. They play a crucial role in soil nutrient dynamics by recycling significant amounts of nutrients. However, harvesting operations can lead to soil depletion if a large amount of biomass is collected. Therefore, chestnut trees can prevent soil nutrient depletion if efficiently managed. Furthermore, litterfall enhances soil fertility, which improves the production and growth of chestnut coppices, and ultimately contributes to carbon sequestration. On average, mature chestnut high-forest stands (with a density of 360 to 1,260 trees per hectare and an age range of 55 to 73 years) restore approximately 4.9 Mg of dry matter per hectare annually and contribute 2.6 Mg of carbon per hectare per year to the soil (Patrício et al., 2012), highlighting the importance of chestnut trees in the annual restitution of nutrients through litterfall.

4. Growth and yield models

a. Description of empirical models vs. possess-based models

Species can thrive in different areas based on the environmental changing conditions, but also depending on many factors that influence their growth and development. The key to an efficient forest management is to identify these factors that influence the silvicultural ecosystems. Many techniques have been developed to assess and control the growth of individual trees or forest stands taking into account numerous environmental elements (Bosela et al., 2023). Although several process-based growth models, such as CO2Fix model (Schelhaas et al., 2004), have been developed, statistical models remain the most commonly applied for analyzing collected data from field studies and remote sensing. In environmental science, and forest ecology fields, linear regressions and advanced modelling techniques are commonly used to identify for

example the relationship between environmental factors related to tree growth and predict how the environmental changes like climate change will affect a forest stand and its productivity. These are tools that have been known to provide insights into decision making regarding forest management practices. But with the fast data sciences development and the use of machine learning techniques, it is brought to consideration that these techniques are a more powerful tools.

To predict and assess tree growth and stand productivity, we can use two categories of models: empirical models and process-based models. The key difference between them is that process-based models incorporate biological mechanisms to predict growth under varying conditions, while empirical statistical models rely on data to establish relationships between variables. According to Irauschek (2021), forest simulation models are essential tools for evaluating medium to long-term management strategies in silviculture. However, with the growing risk posed by climate change, the role of model-based decision support and statistical models is becoming a topic of increased discussion. These models can simulate real-world systems and processes or predict various scenarios, aiding decision-making regarding different forestry topics. Nonetheless, they need to be updated to reflect the new realities of climate change. Naturally, ecophysiological models have an advantage in early adaptation due to their dynamic nature.

Empirical models rely on historical data, often from decades ago, raising concerns about the quality of this data and the accuracy of measurements for the future prediction. This dependence on past data may limit the model's abilities to predict future scenarios, especially given the high complexity of forest ecosystems and changing environmental dynamics. In contrast, process-based models simulate the biological and physical processes that drive stand productivity. These models can incorporate critical elements, such as climate conditions, improving the accuracy of simulations. The growing need to evaluate the productivity of chestnut forests and optimize carbon sequestration potential in coppices requires a clear understanding of both model types, considering their limitations and key strengths, to better assess the impacts of environmental changes on chestnut coppices under different management practices.

b. CO2Fix Model for quantifying carbon sequestration

Despite the efforts to implement climate change mitigation policies, GHG emissions continue to rise. As a result, forest management strategies have become a critical area of study (Prada et al., 2016). According to the authors, quantifying carbon sequestration is essential to understand how much carbon is stored in forest components, and for evaluating their role in mitigating

climate change by reducing atmospheric CO2. Qin & Deng (2023), emphasize the importance of determining how forests sequester CO2. Forest capture through the growth of trees, which store carbon in their biomass, soil, and wood products. This process implies that the ecosystem's capacity to absorb and store carbon increases through photosynthesis.

According Schelhaas et al. (2004), the CO2Fix model is a carbon accounting tool for forest ecosystems, consisting of six modules: biomass module, soil fill, forest products, biomass energy, economic and carbon accounting modules. The model operates at a hectare scale with a time step of one year. It is primarily used to simulate forest ecosystems, including biomass and soil carbon stocks, as well as carbon dynamics between these components and forest products. Additionally, the model simulates the financial aspects of forest management, such as expenditures, revenues, and carbon credits earned under different carbon accounting methods. The CO2Fix model is highly adaptable, with a wide range of applications, and has shown good simulation results across various climates and forest stand types (Schelhaas et al., 2004).

The CO2Fix model allows for simulations across multiple rotation scenarios. It has been applied to various types of forests, including European forests, tropical forests, plantations, monocultures, and coppices. The carbon model converts volumetric net annual increment data, allocation, turnover rates, forest management and wood products into annual carbon stocks. This makes CO2Fix model a powerful tool for assessing the impact of different management practices and exploring the substitution effect of wood products (Qin & Deng, 2023).

Detailed instructions and guidelines on the application and parameterization of the model can be found in the model's manual, which serves as a comprehensive reference for users.

c. Model structure according to CO2FIX V 3.1 manual (Schelhaas et al., 2004)

CO2FIX V 3.1, according to Schelhaas et al. (2004), is an ecosystem-level simulation model that quantifies the carbon stocks and fluxes in the forests using the so-called full carbon accounting approach. In other words, calculating changes in carbon stocks in all carbon pools over time. The model has been programmed in C++ using an object-oriented programming environment and is divided in six main modules (Figure 9):

- Biomass module
- Soil module
- Products module
- Bioenergy module

- Financial module
- Carbon accounting module

The total carbon physically stored in the system at any time (CT_t) is defined as:

$$CT_t = Cb_t + Cs_t + Cp_t \ (Mg\ C/ha)$$

Where Cb_t is the total carbon stored in living (above plus belowground) biomass at any time 't' ($Mg\ C/ha$),

Cs_t is the carbon stored in soil organic matter ($Mg\ C/ha$),

And Cpt is the carbon stored in wood products ($Mg\ C/ha$)

The bioenergy module does not represent a carbon stock; rather, it calculates the impact of using wood or wood waste for energy generation. In this context, fossil fuels are replaced with CO2-neutral fuels, which can be considered as avoided emissions. These avoided emissions can be expressed in carbon equivalents and added to the total stock in the system to assess the overall effect of the simulation on the atmosphere (Schelhaas et al., 2004). Total atmospheric effect A is calculated as follows:

$$A = CT_t + Cbio_t \ (MgC/ha)$$

Where A represents the total atmospheric effect, and $Cbio_t$ refers to the avoided emissions due to bioenergy use.

The carbon accounting module monitors all fluxes to and from the atmosphere, assessing the impact of selected scenarios through various carbon accounting approaches. The financial module evaluates the profitability of different scenarios by considering the costs and revenues associated with management interventions. The model simulates carbon stocks and fluxes in trees, soil, and, for managed forests, wood products. Additionally, it accounts for financial costs, revenues, and carbon credits based on various accounting systems. All simulations; covering stocks, fluxes, costs, revenues, and carbon credits, are conducted on a per-hectare basis with annual time steps.

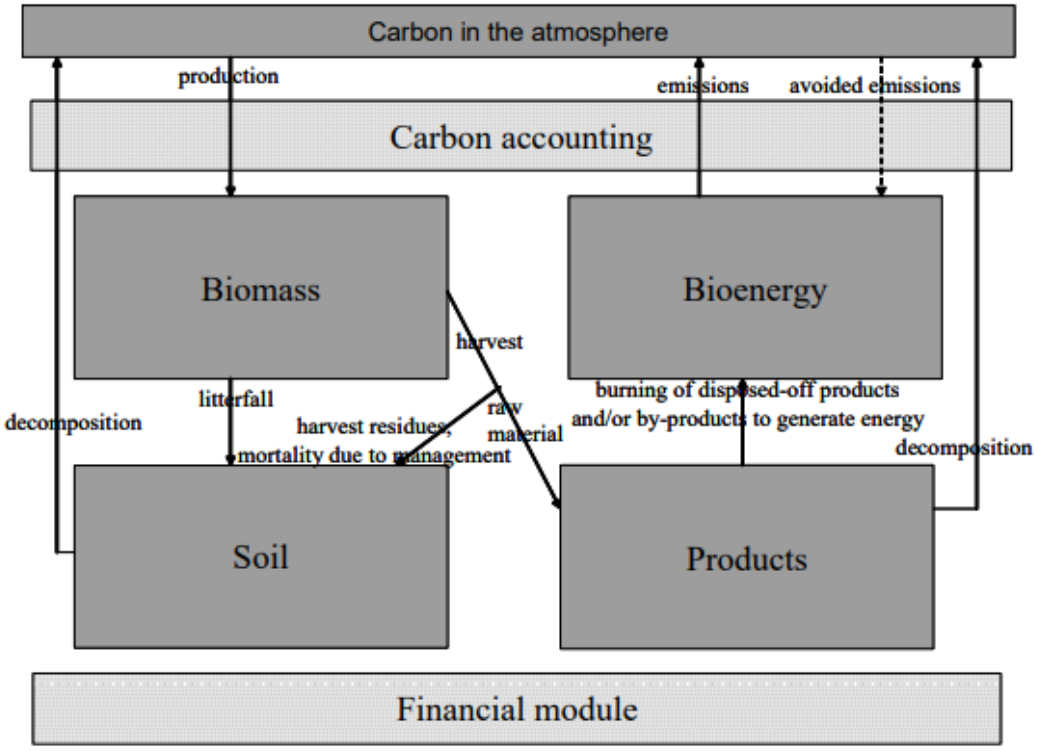


Figure 9 : The modules of CO2FIX V 3.1. (adapted from Schelhaas et al., 2004).

(1) Biomass module

Carbon stocks and fluxes in forest biomass, both above and below ground, are estimated using a 'cohort model' approach. In this model, a cohort represents a group of trees or species with similar growth characteristics, treated as a single unit. Examples of cohorts include (Schelhaas et al., 2004):

- Successional groups in a natural forest (e.g. pioneers, intermediate, and climax species);
- Species in mixed forests (e.g. mixed pine-oak forests);
- Strata in a multi-strata agroforestry system (e.g. understory, middle layer, upper layer).

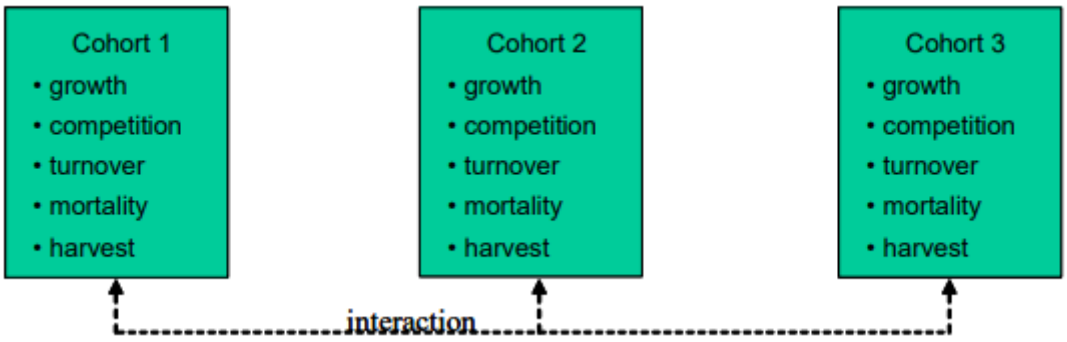


Figure 10 :Process within and interaction between cohorts (adapted from Schelhaas et al., 2004).

The carbon stored in living biomass (Cb_t) of the whole forest stand, can then be expressed as the sum of the biomasses of each cohort, i.e.,

$$Cb_t = \sum Cb_{it}(Mg\ C/ha)$$

where $Cb_{it}$is the carbon stored in the living biomass of cohort 'i' at time 't' ($Mg\ C/ha$).

For each new time step, Cb_{it} is calculated as the balance between the original biomass, plus biomass growth (Gb_{it}), minus the turnover of branches, foliage and roots (T_{it}), minus tree mortality due to senescence (MS_{it}), minus harvest (H_{it}) minus mortality due to logging (Ml_{it}), i.e.,

$$Cb_{it+1} + 1 = Cb_{it} + Kc\,[Gb_{it} - MS_{it} - T_{it} - H_{it} - Ml_{it}\,]\,(MgC/ha)$$

where Kc is a constant to convert biomass to carbon content (Mg C per Mg biomass dry weight).

CO2FIX (Schelhaas et al., 2004), distinguishes four compartments of tree biomass: stem (including bark), foliage, branches, and roots. To simulate Gb_{it} the model uses the growth rate of stem volumes (gross annual increment) as input, which can be obtained from yield tables. Based on this stem volume growth rate the model calculates growth rates for foliage, branches and roots using time-dependent allocation coefficients. Consequently, volume growth (in m3/ ha/ yr) serves as the primary input, and an allometric is employed to derive biomass increments of the main biomass components from this stem volume growth. These growth rates are subsequently adjusted based on interactions within the cohort and between different cohorts. To account for variations in site quality, yield tables for good, medium and poor site conditions may be utilized, with other growth-related parameters adjusted accordingly. Mathematically:

$$Gb_{it} = (Kv_i\ Ys_{it}\ (1 + \Sigma\ (F_{ijt}))) * Mg_{it}\ (Mg\ ha^{-1}yr^{-1})$$

where Kv_i is a constant to convert volume yields into dry biomass (basic wood density, in Mg dry biomass per m3 of fresh stemwood volume) for each cohort 'I'. Ys_{it} is the volume yield of stem wood for each cohort 'i' (m3/ ha/ yr), F_{ijt} is the biomass allocation coefficient of each living biomass component 'j' (foliage, branches, and roots) relative to stems, for each cohort 'i' at time 't' (Mg per Mg stem wood), and $Mg_{it}$is the growth modifier due to interactions among and within cohorts (dimensionless).

According to Schelhaas et al. (2004), the model provides two alternative ways to define stem growth of each cohort:

- as function of tree or stand age (conventional yield tables)
- as a function of the cohort total and maximum aboveground biomass.

The latter input option has been included because, in tropical forests, tree growth is often diameter-dependent rather than age-dependent. To model the carbon stored and accumulated in multi-cohort stands, CO2FIX adjusts the growth of each cohort based on interactions among trees. This adjustment is necessary because the growth of trees within a cohort is affected by the presence of other trees (Schelhaas et al., 2004).

This biomass module has been used in many trials to estimate biomass production and carbon sequestration in forest ecosystems. For instance, in a study conducted in sweet chestnut coppice stands in Asturias, Spain by Prada et al. (2016), the module was used to simulate carbon storage and biomass growth across different biomass components (stems, branches, leaves, and roots). The study employed specific data for sweet chestnut, such as a wood density of 0.584 Mg /m^3 and a carbon content of 48.4%, to calibrate the biomass module, which shows the model's adaptability to specific species and regional conditions.

(2) Soil Module

The soil module in the CO2FIX model (Schelhaas et al., 2004), plays a crucial role in simulating the decomposition and carbon dynamics in well-drained soils. It is composed of three litter compartments and five decomposition compartments, reflecting the complexity of soil carbon processes.

Litter is generated in the biomass module through various processes such as biomass turnover, natural mortality, management mortality, and logging slash. In the soil carbon module, this litter is categorized into non-woody litter (foliage and fine roots), fine woody litter (branches and coarse roots), and coarse woody litter (stems and stumps). A distinction is made between fine and coarse roots based on the proportion of branches and foliage litter since the biomass module does not differentiate between these root types (Schelhaas et al., 2004). According to the authors, each litter compartment has a fractionation rate that determines the proportion of its contents released to the decomposition compartments during a time step. For non-woody litter, this rate is set to 1, indicating that all contents are released in a single time step, whereas woody litter compartments have a fractionation rate less than 1. The soil component of CO2FIX is based on the Yasso model.

Based on the chemical composition of the litter, it can decompose to many components (extractives, celluloses, and lignin-like substances). The rate at which each of these compartments decomposes determines how much of its contents will gradually break down overtime with the influence of environmental factors such as temperature and water availability.

When applying the CO2FIX model to sweet chestnut stands in Asturias (Prada et al., 2016), the soil module was parameterized using the Yasso model. The model utilized climate data and litter quality information to stimulate litter decomposition and residue harvesting. A leaf turnover rate of 1 was estimated, assuming all leaves fall within one year, as chestnut is a deciduous species, Branch turnover was calculated considering 0.40 Ton/ha of carbon to the soil. Stem turnover was assessed by including trees that had fallen between the inventory and the census of dead trees.

(3) Products Module according to CO2FIX V 3.1 manual (Schelhaas et al., 2004)

The products module of CO2Fix (Schelhaas et al., 2004) monitors carbon flow post-harvest. During the harvest year, carbon undergoes multiple intermediate processing and allocation steps before being assigned to end products, the millsite dump, or transferred to the bioenergy module. When end products reach the end of their lifespan, they can be recycled, sent to a landfill, or used for bioenergy, all managed within the bioenergy module (Figure 11).

According to Schelhaas et al. (2004), carbon is released into the atmosphere through decomposition at the millsite dump, in landfills, or via the bioenergy module. The products module uses stem and harvested branch biomass as inputs and categorizes end products into three groups: long-term, medium-term, and short-term products. Each commodity, such as sawn wood, boards and panels, and pulp and paper, is allocated to one of these end product categories. Process losses can be reused in 'lower grade' production lines, used for bioenergy, or disposed of at the mill site.

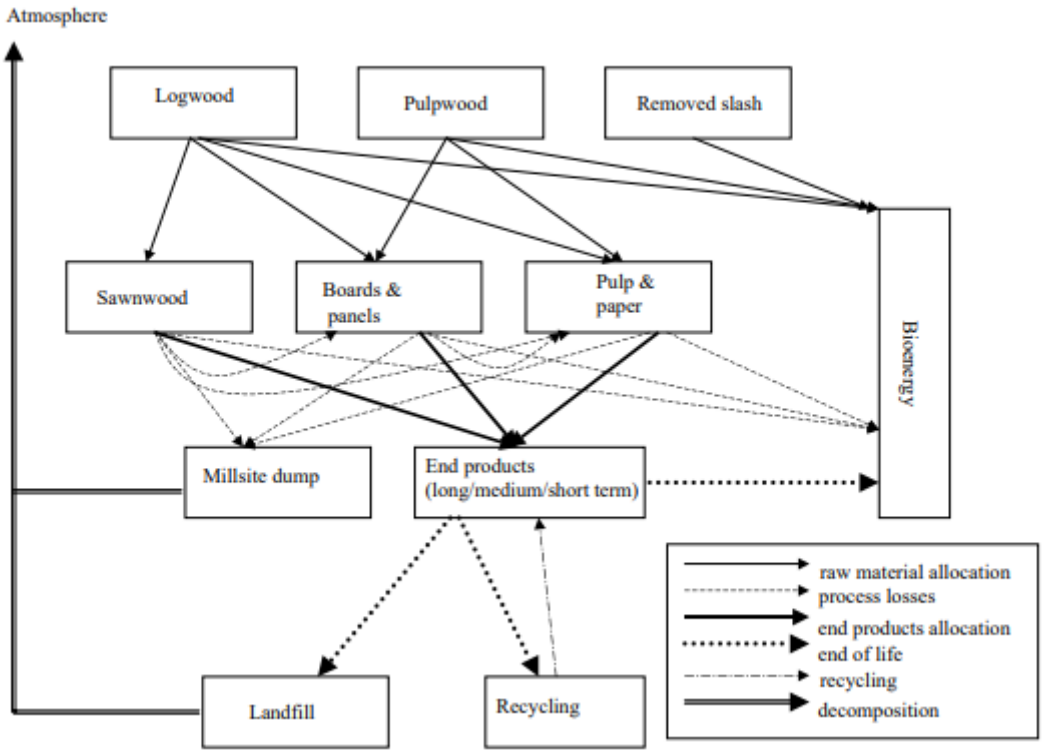


Figure 11 : Outline of the wood products module (adapted from Schelhaas et al., 2004).

When applying the CO2FIX model to chestnut coppices in Asturias, Spain (Prada et al., 2016), data from the region's largest sawmill, which processes 74% of the local chestnut sawn timber, was used. This sawmill produces various products, including beams, planks, poles, and firewood, based on log size. The products module categorized these wood products by their expected lifespans: long-term products (beams) with a 40 years lifespan, medium-term products (poles and planks) with 15 years, and short-term products (firewood) with 1 year.

d. Model initialization and estimation details according to CO2FIX V 3.1 manual (Schelhaas et al., 2004)

To start the CO2FIX model V 3.1, double-click the CO2FIX icon. The first step involves creating a new case study or opening an existing one. Once a case study is opened, all menu options and icons will become active. Figure 12 displays the menu interface of the CO2Fix program.

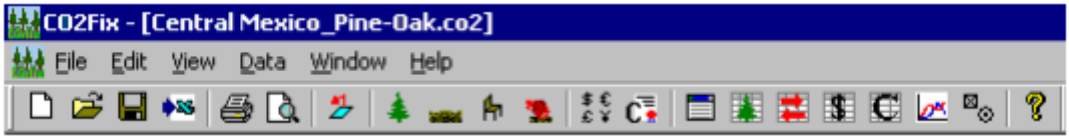


Figure 12 : Main menu options and icons (adapted from Schelhaas et al., 2004).

From left to right, the icons display the following (alternatively, the drop-down menus ‘File’, ‘Edit’, etc., can also be used):

- Six standard windows icons;
- Seven icons representing the main menus for parameterization (general parameters, biomass module, soil module, products module, carbon accounting module, and financial module);
- ‘New window’ icon that enables the opening of multiple case studies simultaneously;
- Six icons to viewing output in various formats;
- An ‘About’ icon.

Clicking on the General Parameters icon opens a dialogue screen with four tabs: Comments, Scenario, General Parameters, and Cohorts (Figure 13). The Comments tab allows for the entry of any relevant information, such as data origin and case study location. The Scenario tab facilitates the definition of different scenarios within the same case study. The General Parameters tab is for inputting essential data to describe the case study and select simulation methods. In the Cohorts tab, users can specify the name and type of cohorts to be simulated.

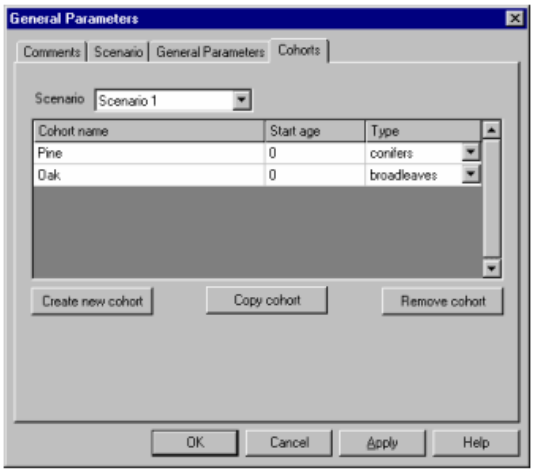


Figure 13 : Cohorts screen in main General parameters (adapted from Schelhaas et al., 2004).

According to the CO2Fix model manual (Schelhaas et al., 2004), many input screens require data to be entered in a table format, which is typically visualized in a graph adjacent to the table. During simulations, CO2FIX performs linear interpolations between data points. If the maximum value is exceeded, the last data point's value will be used. In the biomass module, the primary driving factor for each cohort is the stemwood production measured in volume per hectare. Fluxes into other biomass compartments (roots, branches, foliage) are determined based on their growth relative to stemwood production and their respective carbon contents.

In addition to standard monospecies plantations, the cohort model allows for the modeling of multi-species and uneven-aged stands. Cohorts can be defined in the General Parameters main menu under the Cohorts tab. This screen enables the definition of the number of cohorts forming the stand, the starting age of each cohort, and whether the species is coniferous or broadleaved. This information is crucial for characterizing the quality of litter input to the soil module.

The growth method for the simulation can be selected in the General Parameters main menu under the General Parameters tab. The selected method will apply to all cohorts and scenarios within the simulation. If growth based on aboveground biomass is chosen, the Maximum biomass in the stand box must also be filled out. Additional options in this tab include selecting the competition method, how management mortality is accounted for, and the duration of the simulation.

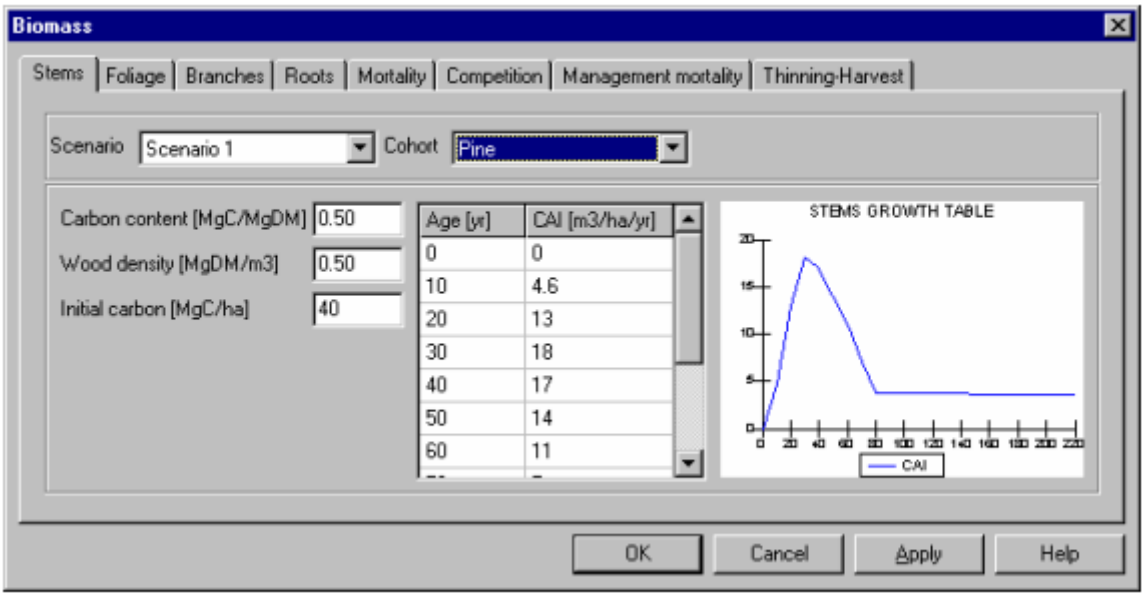


Figure 14 : Stems parameterization screen in main menu biomass (adapted from Schelhaas et al., 2004).

The parameterization of the stem compartment is conducted in the Biomass main menu under the Stems tab (Figure 14). This figure provides an example of how to parameterize the Stems compartment using the age-related growth method. The stem volume increment is specified in 5-year intervals. In addition to the volume increment, it is necessary to provide the carbon content of dry matter, the basic wood density (dry matter per fresh volume), and any carbon that was initially present on the site. Each of the three compartments: Foliage, Branches, and Roots, has a separate tab within the Biomass menu. For each cohort in every scenario, the allocation to these compartments must be specified relative to the dry matter growth rate of the stems. The parameterization of natural mortality (expressed as a fraction of the standing

biomass) is carried out in the Biomass main menu under the Mortality tab. The user has two options for modeling mortality resulting from logging damage:

- Mortality as a function of total biomass removed, i.e., the mortality of the remaining trees in all cohorts is uniform and proportional to the remaining biomass of each cohort (default).
- Mortality as a function of biomass removed from each cohort, i.e., the mortality of all the remaining trees in all the remaining cohorts depends on the degree of logging of the cohort logged.

The selection between these methods must be made in the General Parameters main menu under the General Parameters tab. The other parameters can be found in the Biomass main menu under the Management Mortality tab (Figure 15).

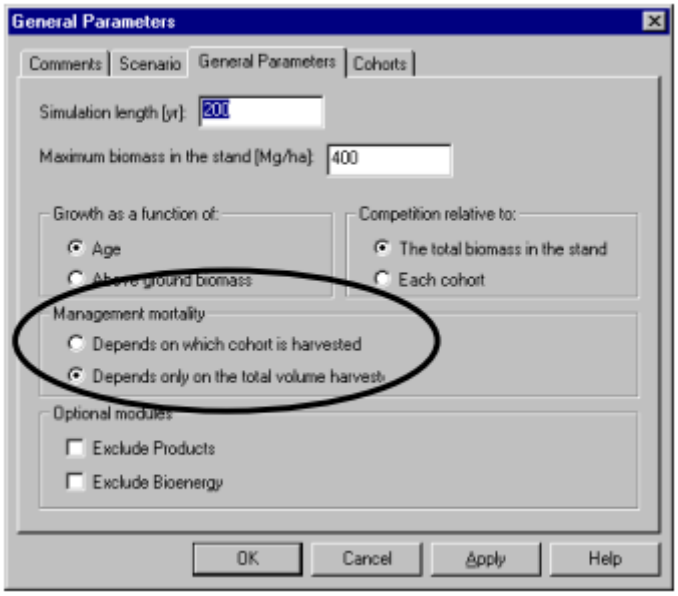


Figure 15 : General parameters screen, with in this case management of mortality as a function of the total volume harvested (adapted from Schelhaas et al., 2004).

Within CO2FIX, two types of management interventions can be performed: thinning and final felling. Thinning is characterized by the following parameters:

- Age at which the intervention takes place;
- Intensity of the intervention (fraction of cohort biomass removed);
- Allocation of the biomass removed to different 'raw material' classes as slash, logwood and pulpwood.

Final felling can be simulated in the model as a thinning operation where 100% of the biomass is removed. Management parameters are located in the Biomass main menu under the Thinning-Harvest tab (Figure 16).

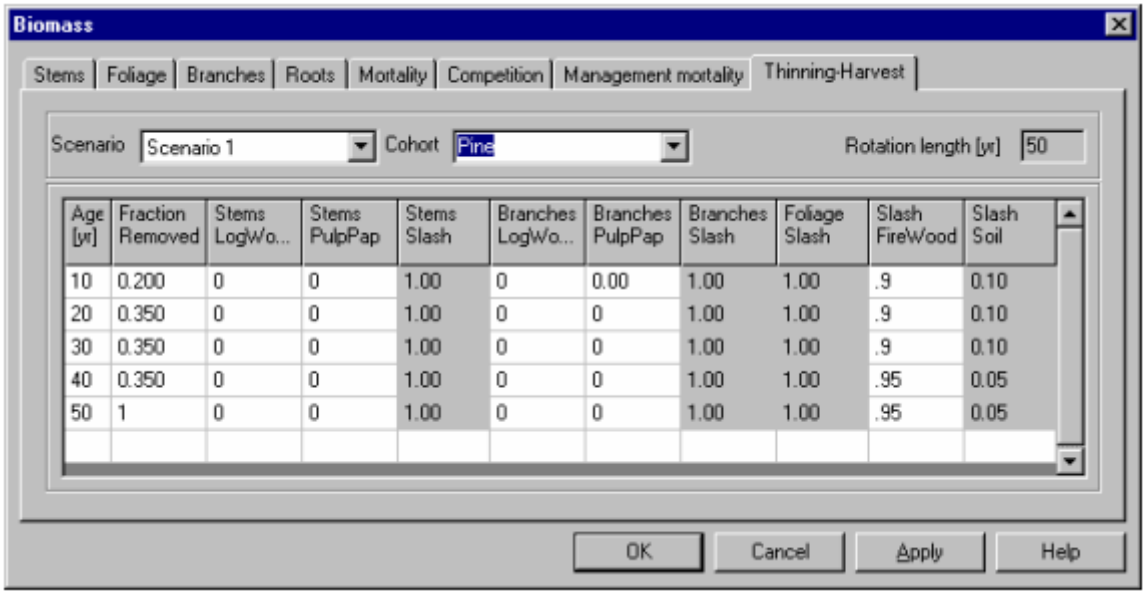


Figure 16 : Thinning and final harvesting table (adapted from Schelhaas et al., 2004).

The parameters for the soil module are located under the Soil main menu, which contains two tabs: General Parameters and Cohort Parameters. In the General Parameters tab, the user must input climate parameters for the site, including the effective temperature sum (degree days above zero) over the year (°C d), precipitation during the growing season (mm), and potential evapotranspiration in the growing season (PET, mm). CO2FIX can calculate degree days above zero and potential evapotranspiration based on the mean monthly temperatures (Figure 17).

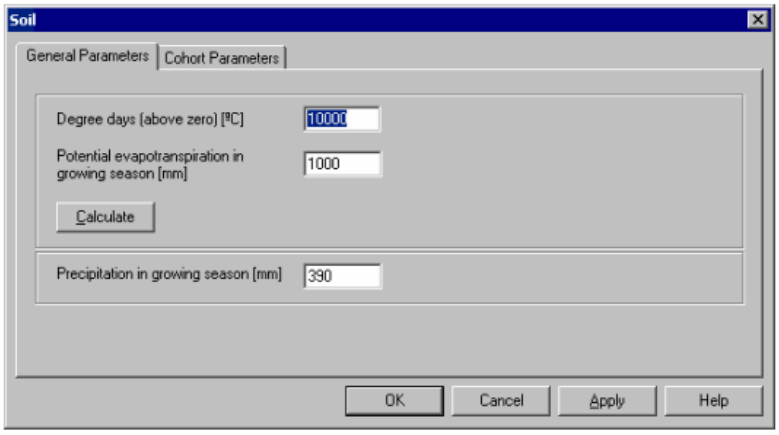


Figure 17 : Main window for the soil module (adapted from Schelhaas et al., 2004).

All parameters related to the products module are available in the Products main menu. The first tab, Production Line, contains parameters for raw material allocation and process losses.

The top part of the window deals with raw material allocation, where pulpwood and logwood are distributed among the commodities: sawnwood, boards and panels, pulp and paper, and bioenergy. The firewood/bioenergy value is automatically adjusted so that the sum of the fractions equals 1. In the bottom part of the window, the user can specify how process losses are handled within the production line for each commodity (Figure 18).

Figure 18 : Parameterizing the products module: raw material allocation and processing losses (adapted from Schelhaas et al., 2004).

The second tab, End Products, contains parameters for the allocation of end products and the end-of-life process. In the top part of the window, the user can define the fraction of each commodity (sawnwood, boards, paper) that is allocated to long, medium, and short-term products. These allocations must sum to 1, as the short-term fraction is calculated as 1 minus the sum of the long-term and medium-term fractions. The bottom part of the window specifies the fate of the products at the end of their lifespan. The user defines the fractions of discarded products that are recycled or burned for bioenergy, while the remaining portion is assumed to be disposed of in a landfill (Figure 19).

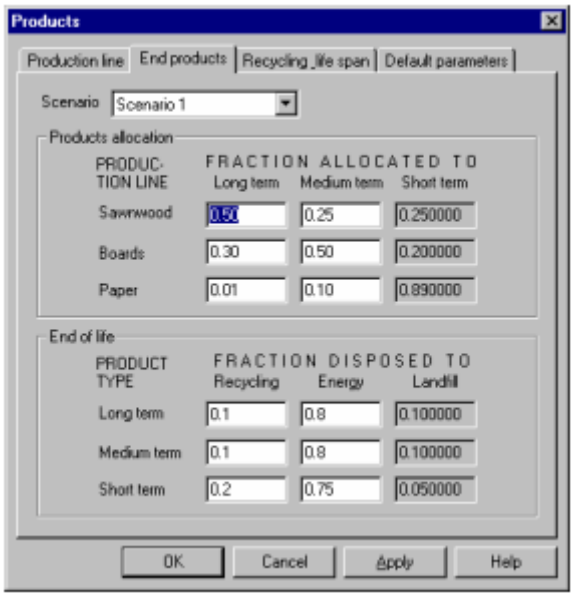


Figure 19 : Parameterizing the products module: life span allocation and end-of-life disposal (adapted from Schelhaas et al., 2004).

The third tab, Recycling Life Span, contains the life spans of the three product groups, the landfill, and the millsite dump, as well as the parameters for the recycling process. The top part of the window allows the user to configure the recycling between different life span groups. The bottom part provides the parameterization for the life spans of the three product groups, the landfill, and the millsite dump. The life span parameter represents the half-life, meaning that a life span of 15 years indicates that 50% of the original carbon remains after 15 years (Figure 20).

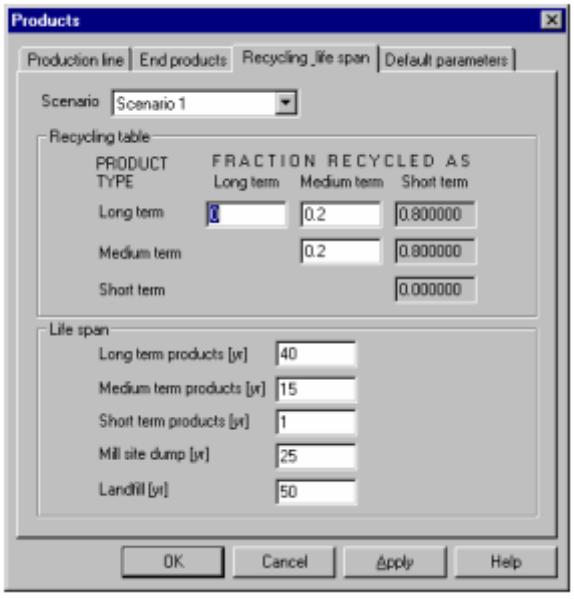


Figure 20 : Parameterizing the products module: way of recycling and life spans (adapted from Schelhaas et al., 2004).

Finally, when we click ‘Apply’ or ‘OK’, the simulation is immediately updated.

e. Outputs of the CO2FIX model

Using the CO2Fix model simulations, we can generate a variety of results that are crucial for understanding carbon sequestration and dynamics within the forest ecosystem. These outputs can be sorted into several key types, including carbon stocks and fluxes in various pools (biomass, soil, products), as well as financial and bioenergy metrics. The model can output biomass and carbon separately in above ground and below ground tree components, since it simulates the accumulation and distribution of carbon within different biomass components such as trees and crops, as well as within the soil. For instance, in a study conducted across various districts in India, the CO2Fix model was applied to simulate tree biomass over a 30-year period (Gupta & Dhyani, 2013). The results indicated a substantial increase in biomass carbon by the end of the simulation. Tree biomass (above and below ground) during the simulation period increased from 2.56 to 8.24 Mg DM/ ha in Sultanpur, 2.45 to 8.22 Mg DM/ ha in Dinajpur, and from 2.88 to 4.67 Mg DM/ ha in Ludhiana district. These findings demonstrate the model’s ability to predict changes in carbon stocks over time, which is crucial for assessing the long-term sustainability of different land use practices.

Another key output of the CO2FIX model is the rate of carbon sequestration, especially within the soil component. A study conducted in India, Gupta & Dhyani (2013), demonstrated that the carbon sequestration rates varied across districts, with higher carbon rates observed in areas with denser and fast-growing trees. This variation highlights the CO2Fix model’s ability to account for the effects of different management strategies on carbon sequestration, while also tracking the dynamics of carbon through various transfer pools, such as litterfall and root turnover. These insights are important to understanding the overall carbon balance within the ecosystem.

f. CO2Fix calibration

To properly calibrate the CO2Fix model many input parameters should be available in order to deliver accurate results. According to Schelhaas et al. (2004), the cohort wise values for the stem-CAI (current annual increment in $(\mathrm{m}^3/ha/\mathrm{yr})$), in addition to relative growth of the foliage, branches, leaf and root with respect to the stem growth over the years, are crucial elements for running the model. Turnover rates for different biomass components (foliage, branches, and roots) should be taken into account, also climate data of the site including annual precipitation in mm and monthly values of minimum and maximum temperatures in °C. The

model's inputs include the initial surface soil organic carbon (Mg C/ha) and the rotation length for the tree species. These parameters help define the baseline carbon stocks for the stands trees, but to effectively run the CO2Fix model, both primary and secondary data are required. Primary data might include details such as the identification of existing tree species, the DBH, the productivity of crops grown on farmlands, the area coverage. Secondary data, that is also important involves the growth rates of tree biomass different components (stem, branch, foliage, root) for various species on an annual basis, as well as data regarding the productivity of different crops grown in the studied region. All this data combined will ensure the accuracy of model's outputs that capture carbon dynamics (Gupta & Dhyani, 2013).

III. Material and methods

A. Characterization of the study area

1. Geographical situation

The municipality of Mogadouro (Figure 21), is located in the Trás-os-Montes region of northeastern Portugal, within the district of Bragança. It is bordered by the municipalities of Vimioso, Macedo de Cavaleiros, Alfândega da Fé, Torre de Moncorvo, and Freixo de Espada à Cinta, while the Douro River separates it from the Spanish province of Castilla y León. The Douro and Sabor rivers naturally define the territory, with much of it lying within the fertile Mirandês Plateau, an extension of the Iberian Meseta. This area supports diverse agriculture, including cereals like wheat, oats, and rye, alongside cattle and sheep farming. Sheltered valleys with microclimates nurture vineyards, olive, orange, and almond orchards, as well as other Mediterranean crops. The landscape features granite escarpments and schist formations, particularly around the Douro and Sabor basins, with average altitudes reaching around 700 meters, though peaks like the 'Cimas de Mogadouro' rise up to 900 meters above sea level (Mendes et al., 2020).

Figure 21 : Map of Mogadouro region location in Portugal (adapted from Tschubby (2020) via Wikimedia, https://commons.wikimedia.org/w/index.php?curid=8764596).

2. Climate characteristics

Mogadouro, located in northern Portugal, experiences a Mediterranean climate with hot, dry summers and cold, wet winters. The average annual temperature is 12.9°C, with July being the hottest month, reaching a maximum of 29.1°C, while January is the coldest, with an average low of 1.6°C. The region receives an average annual rainfall of 658.2 mm, with the wettest month being November, averaging 90.7 mm of rain. Summer months, especially July, are dry, with only 15.6 mm of rainfall. Overall, Mogadouro has between 80 to 100 rainy days per year, with occasional snowfall in winter. This climate supports the region's diverse agricultural activities, benefiting from the wet season from September to May (IPMA, 2023).

3. Geology and pedology

The soil at the trial site is classified as lithic, non-humic, derived from the quartz-schist complex of the Upper Ordovician, with a depth of 70 cm. It has an acidic pH between 4.5 and 5.0, with a sandy loam texture at the surface and a clay loam texture at depth (Maia, 1988; Patrício, 1996).

B. Characterization of the trial

A trial conducted in the Mogadouro region, Portugal, was designed to evaluate the carbon sequestration and storage potential in chestnut coppices, focusing on the effects of different shoot densities per stool. The trial was primarily established in a chestnut plantation located in an area known as 'Cimas de Mogadouro.' The plantation was set up with a spacing of 4x2 m. At 7 years of age, the young high-forest chestnut stand was transformed into a coppice by cutting down the trees. The trial was designed as a completely randomized block experiment, consisting of 4 treatments and 3 blocks, totaling 12 plots, each containing 70 plants arranged in 7 rows of 10 plants each. The plot area is approximately 560 m². The treatments randomly applied in each block were as follows: T1 – A - Maintenance of one shoot per stump; T2 – B- Maintenance of three shoots per stump; T3 – C - Maintenance of five shoots per stump; T4 – D- Control (maintained as high forest). Additional details regarding the trial can be found in Patrício (1996).

C. Dendrometric parameters

The database used in this study was derived from successive measurements of the aforementioned trial over time. This analysis considers the dendrometric data obtained following the establishment of the coppice at ages 2, 4, and 12 years. The database includes the

individual diameters of the shoots per stump, recorded at 30 cm above ground level (D0.30, in centimeters) and at breast height (d, in centimeters) (when the height growth exceeded 1.30 m, namely in the measurements at 4 and 12 years old), as well as the total height of the shoots per stump (h, in meters), number of shoots per stump and per plot and number of stumps per plot. Table 2 provides a sample from the larger dataset used in the study, only 5 rows are shown here for illustration purposes. These data were used to estimate the total volume (Vtotal) by applying Smallian's formula for the log section between the stump and DBH, considering the stump as a cylinder (V0.30) and the crown as a cone (Vcrown), along with specific volume equations for chestnut coppices. Since the shoots had generally not yet reached a height of 1.30 m by ages 2 and 4, the volume was calculated treating the stump as a cylinder ($V_{0.30}$) and the crown as a cone (V_{crown}). In total, a dataset containing 7,394 observations, resulting from successive measurements over time, was utilized.

Table 2 : Sample of data from the full dataset containing over 7,394 entries (only 5 rows shown per measurement date) (Author's own work).

Age	Local	Block	Plot	Treatment	Line	N° Plant	N° Shoots	Selected Shoots	h(m)	D0.30(cm)	d(cm)
2	MOG	1	A	T1	1	141	1	a	1.20	2.0	
2	MOG	1	A	T1	1	142	1	a	1.10	1.7	
2	MOG	1	A	T1	1	143	1	a	1.11	2.1	
2	MOG	1	A	T1	1	144	1	a	1.30	2.1	
2	MOG	1	A	T1	1	145	1	a	0.78	0.9	
4	MOG	1	A	T1	1	141	1	a	1.52	2.7	
4	MOG	1	A	T1	1	142	1	a	1.30	2.4	
4	MOG	1	A	T1	1	143	1	a	1.65	2.6	
4	MOG	1	A	T1	1	144	1	a	1.90	2.8	
4	MOG	1	A	T1	1	145	1	a	1.66	1.7	
12	MOG	1	A	T1	1	141	1	a	1.70	4.6	1.2
12	MOG	1	A	T1	1	142	1	a	1.90	2.3	1.1
12	MOG	1	A	T1	1	143	1	a	1.66	2.2	1
12	MOG	1	A	T1	1	144	1	a	2.35	5.0	1.5
12	MOG	1	A	T1	1	145	1	a	2.55	3.5	2.2

h: Tree height (m), **D(0.30)**: Diameter at 30 cm (cm), **d**: Diameter at breast height (cm).

For the 12th year of the trial, the database included key dendrometric parameters such as the total number of shoots, hg (mean height in meters), hdom (dominant height in meters), dg (quadratic mean diameter in centimeters), ddom (dominant diameter in centimeters), and G (basal area m²/ha). These measurements were recorded for each block and treatment, providing detailed information on the development of the chestnut coppices (Table 3).

The total number of shoots gives an overview of the density and vigor of the coppice regrowth, which is directly linked to biomass accumulation and carbon sequestration potential, hg and hdom provide insights into the overall and dominant growth of the trees, which is important for assessing the forest's development and dynamics within each plot, dg and ddom characterize the horizontal growth of the trees, with mean values representing the general growth trend and dominant values reflecting the most vigorous trees, which are the key contributors to overall biomass production, G is also a crucial parameter in forest management, representing the cross-sectional area of all trees per hectare. It is directly related to the stand's capacity for wood production and carbon storage, as basal area correlates with tree volume and biomass.

Table 3 : Dendrometric parameters at 12th year (Author's own work).

Block	Treatment	Total number of shoots	hg(m)	hdom(m)	dg(cm)	ddom(cm)	G(m2/ha)
I	T1	247	2.8	4.34	2.3	6.5	1.935
I	T2	251	3	4.19	2.6	5.8	2.485
I	T3	274	3.3	4.8	3.1	6.4	3.693
I	T4	229	3.2	4.53	3	6.5	2.88
II	T1	253	2.8	4.16	2.2	6.3	1.691
II	T2	220	3.5	4.95	3.6	6.8	3.969
II	T3	188	2.9	4.19	2.6	5.9	1.688
II	T4	222	2.9	4.68	2.5	7.3	2.019
III	T1	293	3	4.64	2.5	7.5	2.58
III	T2	249	3.7	5.37	3.6	7.6	4.308
III	T3	306	3.3	5.21	3.3	7.6	4.557
III	T4	180	4.4	6.05	4.5	10.1	5.099

hg: Mean height (m), **hdom**: Dominant height (m), **dg**: Mean diameter (cm), **ddom**: Dominant diameter (cm), **G**: Basal area (m^2/ha).

The metrics in table 3, collected per block and treatment, give an idea of the growth dynamics under varying shoot densities, hdom and ddom are particularly useful in identifying the most productive plots in each treatment, while G allows for the quantification of the stand's total growing space and overall forest density. Using these metrics, the CO2FIX model (Schelhaas et al., 2004) can be parameterized to simulate forest structure dynamics based on how different management strategies impact forest productivity.

As a result of analyzing these dendrometric parameters across treatments and blocks, conclusions can be drawn about the relationship between shoot density, tree growth, and carbon sequestration potential, which directly supports the study's aim to quantify chestnut coppices carbon storage capacity.

D. Estimation of volume

To calculate the stem and crown volumes for the chestnut coppice trial, we followed specific formulas based on measured diameters and heights. For the shoots that did not reach a height of 1.30 m at the early ages of 2 and 4 years, the volume was calculated by treating the stump as a cylinder ($V_{0.30}$) and the crown as a cone (V_{crown}) as follows:

$$V_{0.30} = \frac{\pi \, x \, (D_{0.30}/100)2}{4} \text{ x } 0.30$$

where $D_{0.30}$ is the diameter measured at 0.30 m. This formula calculates the cylindrical volume of the stem from the base up to 0.30 m.

For crown volume (V_{crown}), the following formula was applied:

$$V_{crown} = \frac{\pi}{12} \text{ x } (\frac{D_{0.30}}{100})^2 \text{ x } (\text{h} - 0.30)$$

where h is the total height of the shoot in meters, and $D_{0.30}$ the diameter at 0.30 m in centimeters. This calculates the conical section of the crown above the 0.30 m height. The total volume of the shoot corresponds to the sum of the partial volumes.

For the 12th years old, we extended these calculations by including the volume at 1.30 m height ($V_{1.30}$), using the following formula:

$$V_{1.30} = (\frac{\pi \, x \, (\frac{D_{0.30}}{100})^{\,2}}{4} + \frac{\pi \, x \, (\frac{d}{100})^2}{4}) \, x \, \frac{1.30-0.30}{2}$$

where $D_{0.30}$ is the diameter measured at 1.30 m and d the DBH. This formula calculates the average of the sections at 0.30 m and 1.30 m, and uses it to compute the volume of the stem between those heights.

The individual volumes obtained were first used to calculate the volume per plot, and then per treatment, with values expressed per hectare. Based on these values, the volume increments were calculated to parameterize CO2Fix for each treatment.

This extensive dataset was used for estimating and quantifying the biomass and carbon stocks in wood products under different chestnut coppice management types. Furthermore, the data from this trial was applied to calibrate and validate the simulations of the model, ensuring its accuracy in predicting carbon sequestration over time. The model was also employed to simulate carbon dynamics over multiple rotations, enabling the assessment of long-term carbon sequestration trends.

E. Estimation of biomass using allometric equations

Due to the lack of biomass equations for chestnut coppices specific for the study area, available equations from the literature for the species managed as coppice were tested, namely:

1. Menéndez-Miguélez et al. (2013)

To estimate the biomass for chestnut coppice at the stand level, we used equations from Menéndez-Miguélez et al. (2013). These equations provide a comprehensive system for estimating biomass based on stand-level variables, incorporating key characteristics such as dominant diameter, average height of the thickest shoots, and basal area. This enables accurate estimation of biomass components like wood, bark, and crown.

The stand-level equations are reliable for quantifying total biomass and assessing growth and carbon storage potential under different management strategies. By applying this system of equations to data from 12-year-old chestnut coppice stand, we calculated and compared biomass components for each treatment, gaining insights into biomass distribution dynamics.

Biomass equations used in this study:

(1) Wood Biomass Equation:

$$Wwood = b_{01}.d_0^{b11}.G^{b21}$$

Where:

$Wwood$: wood biomass (Ton/ha); d0: dominant diameter (cm); G: basal area (m^2/ha);

b_{01}= 0.8582

b_{11}= 0.8474

b_{21}= 0.5537

(2) Bark Biomass Equation:

$$Wbark = b_{02}.Hdom^{b12}.G^{b22}$$

Where:

$Wbark$: bark biomass (Ton/ha); Hdom: dominant height (m); G: basal area (m^2/ha);

b_{02}= 0.2449

b_{12}=0.4847

b_{22}=0.6431

(3) Crown Biomass Equation:

$$Wcrown = b_{03}.d^{b13}.Hdom^{b23}.G^{b33}$$

Where:

$Wcrown$: crown biomass (Ton/ha); d: dominant diameter (cm); Hdom: dominant height (m); G: basal area (m^2/ha);

b_{03}= 14.31

b_{13}= 1.221

b_{23}= -1.649

b_{33}= 0.4965

By using the equations for wood, bark, and crown, we were able to estimate the total biomass of the chestnut coppice stand at 12 years. Summing these biomass components provided an estimate of the total biomass, which contributes to understanding the growth and carbon sequestration potential of the chestnut coppices.

2. Cutini (2000)

Equations for chestnut coppices from Cutini (2000) for Monte Amiata (Central Italy) were tested in our study. We applied his allometric equations to estimate stem, branch, and total biomass using data from our 12-year-old chestnut coppice trial. These equations enable the estimation of aboveground biomass components using inventory data from our plots, focusing on measurements such as diameter at breast height (1.30 m) and tree height. The allometric model used for biomass estimation is:

$$y = a + bD^2H$$

Where:

y is the dry weight (kg) or volume (dm^3) of each tree; D is the tree diameter (cm) at breast height; H is the tree height (m); a and b are regression coefficients that assume the following values:

- Stem biomass: $a = 1.8898$, $b = 0.0177$
- Branch biomass: $a = 0.9902$, $b = 0.0008$
- Total tree biomass: $a = 2.2607$, $b = 0.0197$

3. Leonardi et al. (1996)

Equations for chestnut coppices from Leonardi et al. (1996) for Spain, France, and Italy were tested in our study. These equations estimate trunk, branch, and total wood biomass using DBH measurements, which were apply to our 12-year-old chestnut coppice data. By utilizing these equations, we aim to evaluate the biomass components of our trial, providing insights into the biomass distribution within chestnut coppice stands.

The equations used for estimating trunk, branch, leaf, and total wood biomass based on DBH:

$$Trunk\ biomass = 0.064\ x\ DBH^{2.401}$$

$$Branch\ biomass = 0.023\ x\ DBH^{2.307}$$

$$Leaf\ biomass = 0.004\ x\ DBH^{2.296}$$

$$Total\ wood\ biomass = 0.080\ x\ DBH^{2.421}$$

4. Ruiz-Peinado et al. (2012)

Root biomass equation for sweet chestnut from Ruiz-Peinado et al. (2012) for Spain was used in our study, as previous authors did not provide equations applicable to root biomass. The data used to develop this equation were collected from representative sites across Spain, covering diverse environmental conditions and cultivation areas.

The root biomass was estimated using the equation:

$$Wr = 0.0211\ .\ d^{2.804}$$

Where Wr denotes the root biomass and d represents the mean diameter at breast height.

In our research, this equation was applied to our 12 years-old chestnut coppice data to accurately estimate root biomass. This allowed for the estimation of root biomass based on the diameter at breast height.

CO2Fix model calibration:

In the calibration of the CO2Fix model for our chestnut coppice trial, we methodically adjusted parameters across the three core modules: biomass, soil, and products to ensure accurate simulation of carbon dynamics.

F. Model validation

Validating the CO2Fix model is crucial for ensuring that it accurately simulates carbon dynamics in chestnut coppices. By comparing the model's predictions with observed data from field trials, we can assess its reliability in estimating stem volume and other key metrics. To enhance and refine the model, this comparing seems to be valuable for further improvement allowing more accurate predictions which can help in the management and the understanding of carbon dynamics within the chestnut coppices systems.

In our study, we compared observed stem volume (Vobserved) with the estimated values (VCO2Fix) generated by the CO2Fix model for different treatments at ages 2, 4, and 12 years.

IV. Analysis of results

A. Estimation of volume

The individual tree volumes were initially aggregated to calculate the volume per plot and subsequently per treatment, with values standardized per hectare (Table 4). From these values, volume increments were determined, providing the necessary parameters to configure CO2Fix for each treatment.

Table 4 : Wood volume (m^3/ha) for each block and treatment across different years (Author's own work).

		Block								
		1	2	3	1	2	3	1	2	3
Age (years)		2			4			12		
Treatment	T1-A	0.2150	0.2118	0.3809	0.5341	0.4599	0.8451	6.5087	5.4857	8.0045
	T2-B	0.3988	0.9245	1.1969	0.9839	2.0345	2.5523	8.5077	12.4617	13.6790
	T3-C	0.7294	0.3160	1.4256	1.9289	0.7917	3.1001	12.0584	5.8679	14.1541
	T4-D	0.7536	0.6095	1.5156	1.3274	1.0324	1.0324	10.7960	7.7966	16.6901

To explore the dataset, namely the difference between treatments, we calculated the mean volume per treatment and age to better understand growth patterns. Then, we determined the standard deviation to assess the variability in volume data, providing more detailed insights into growth rates. Additionally, we computed the coefficient of variation (CV) as a measure of variability, which is particularly useful for comparing data across treatments with different scales (Table 5).

Table 5 : Mean volume, standard deviation, and coefficient of variation per treatment and age (Author's own work).

Age (years)		2			4			12		
parameters		Mean vol. (m3/ha)	Sd	CV (%)	Mean vol. (m3/ha)	Sd	CV (%)	Mean vol. (m3/ha)	Sd	CV (%)
Treatment	T1 - A	0.2693	0.0789	29.3342	0.6130	0.1668	27.2182	6.6663	1.0343	15.5158
	T2 - B	0.8401	0.3312	39.4279	1.8569	0.6525	35.1398	11.5495	2.2075	19.1134
	T3 - C	0.8237	0.4578	55.5820	1.9402	0.9424	48.5728	10.6934	3.5177	32.8964
	T4 - D	0.9596	0.3975	41.4280	1.1307	0.1390	12.2978	11.7609	3.6943	31.4117

Sd: Standard deviation, **CV(%)**: Coefficient of variation (%).

The CAI (Current Annual Increment) for each treatment over the years was calculated to represent the annual volume increase. The CAI is a key metric in forestry and carbon sequestration research. as it provides insight into tree growth rates and their potential for carbon storage. Analyzing the CAI enables the assessment of how effective different treatments are in promoting growth, offering valuable information for identifying the best silvicultural management practices to optimize biomass production and carbon sequestration in chestnut coppices (Table 6).

Table 6 : Current annual increment (CAI) volume per treatment across years (Author's own work).

	Treatments							
	T1 - A		T2- B		T3 - C		T4- D	
Age (years)	Mean volume (m3/ha)	CAI (m3/ha/year)	Mean volume (m3/ha)	CAI (m3/ha/year)	Mean volume (m3/ha)	CAI (m3/ha/year)	Mean volume (m3/ha)	CAI (m3/ha/year)
2	0.2693		0.8401		0.8237		0.9596	
4	0.6131	0.1718	1.8569	0.5084	1.9402	0.5582	1.1307	0.0855
12	6.6663	0.7566	11.5495	1.2115	10.6934	1.0941	11.7609	1.3287

This detailed approach ensures accuracy in interpreting the trial data and allows for meaningful comparisons across years, and treatments. These comparisons were essential for the calibration and validation of the CO2FIX model in this study.

B. Estimation of biomass

In our analysis of chestnut coppices, we evaluated biomass estimates from four different sources: Menéndez-Miguélez et al. (2013), Ruiz-Peinado et al. (2012), Cutini (2000) and Leonardi et al. (1996). These studies provide various equations for estimating different biomass components such as wood, bark, stem, crown, and total biomass. The results obtained from these evaluations are presented in Tables 7 to 10, as shown below.

From our comparison, it appears that the values provided by Cutini (2000) are the most reasonable and aligned with our observations. Cutini's models offer plausible estimates for stem, branches, and total biomass, which closely match our field data and visual assessments. However. we noted that the total biomass values reported by Leonardi et al. (1996) seem quite low compared to what was observed in the trial trees. Additionally, the biomass estimates from Mendez-Miguélez et al. (2012) produced notably high values for total biomass, which appeared disproportionately large relative to our observations.

Given these observations, we will use Cutini's equations for estimating stem, branches, and total biomass in our study, as they provide values that are consistent with our data derived from field observations. For leaf biomass, we will adopt the estimates from Leonardi et al. (1996), as they are reasonable and align well with our findings. By integrating these selected models, we aim to ensure a more accurate and reliable estimation of biomass components in our chestnut coppices.

Table 7 : Estimated total biomass using Menéndez-Miguélez et al. (2013) equations at 12 years (Author's own work).

Block	Treatment	Wwood(ton/ha)	Wbark(ton/ha)	Wstem(ton/ha)	Wcrown(ton/ha)	Wtotal(ton/ha)
I	T1	6.0420	0.7626	6.8047	17.3509	24.1557
I	T2	6.3010	0.8806	7.1816	18.1148	25.2964
I	T3	8.5291	1.2135	9.7426	19.8757	29.6183
I	T4	7.5303	1.0056	8.5360	19.6965	28.2325
II	T1	5.4610	0.6851	6.1461	16.7503	22.8964
II	T2	9.3442	1.2902	10.6345	21.0850	31.7195
II	T3	5.1606	0.6867	5.8474	15.2654	21.1128
II	T4	6.8253	0.8129	7.6383	18.0310	25.6693
III	T1	7.9988	0.9479	8.9467	21.3486	30.2954
III	T2	10.7445	1.4148	12.1594	21.9939	34.1533
III	T3	11.0841	1.4455	12.5296	23.7728	36.3025
III	T4	15.0101	1.6706	16.6808	27.8014	44.4822

Table 8 : Estimation of stem, branch, and total biomass using Cutini (2000) equations at 12 years (Author's own work).

Block	Treatment	Wstem(ton/ha)	Wbranches(ton/ha)	Wtotal(ton/ha)
I	T1	9.4917	4.4198	11.2583
I	T2	10.0793	4.5109	11.9235
I	T3	11.9930	4.9690	14.1181
I	T4	9.8125	4.1434	11.5648
II	T1	9.6215	4.5226	11.4197

Table 8 : Estimation of stem, branch, and total biomass using Cutini (2000) equations at 12 years (Author's own work) (continued)

Block	Treatment	Wstem(ton/ha)	Wbranches(ton/ha)	Wtotal(ton/ha)
II	T2	10.5784	4.0326	12.3919
II	T3	7.5092	3.3769	8.8860
II	T4	8.7635	3.9829	10.3776
III	T1	11.6241	5.2594	13.7609
III	T2	12.1768	4.5734	14.2524
III	T3	13.8022	5.5678	16.2216
III	T4	11.1435	3.4119	12.9085

Table 9 : Estimation of trunk, branch. and total wood biomass using Leonardi et al.(1996) equations for 12 years (Author's own work).

Treatment	Wstem(Ton/ha)	Wbranches(Ton/ha)	Wleaves(Ton/ha)	Wtotal(Ton/ha)
T1	2.0854	0.6930	0.1194	2.6506
T2	2.8446	0.9345	0.1608	3.6243
T3	4.7370	1.5306	0.2629	6.0567
T4	3.6593	1.1860	0.2038	4.6757
T1	1.9199	0.6407	0.1105	2.4380
T2	5.4462	1.7352	0.2976	6.9845
T3	2.1306	0.6999	0.1205	2.7146
T4	2.2898	0.7550	0.1300	2.9152
T1	3.0221	0.9964	0.1716	3.8475
T2	6.1642	1.9639	0.3368	7.9051
T3	6.1470	1.9746	0.3389	7.8695
T4	7.6143	2.3756	0.4064	9.8085

Since the equations for the different biomass components of the tree were adjusted separately, the sum of the biomass components is not expected to match the total biomass estimated by the equation.

Table 10 : Estimation of root biomass using Ruiz-Peinado (2012) equation at 12 years-old (Author's own work).

Block	Treatment	Wroots(Kg/tree)	Wroots(ton/ha)
I	T1	0.2181	0.9618
I	T2	0.3075	1.3783
I	T3	0.5036	2.4639
I	T4	0.4593	1.8784
II	T1	0.1925	0.8697
II	T2	0.7659	3.0088
II	T3	0.3075	1.0324
II	T4	0.2755	1.0921
III	T1	0.2755	1.4414

Table 10 : Estimation of root biomass using Ruiz-Peinado (2012) equation at 12 years-old (Author's own work)(continued).

Block	Treatment	Wroots(Kg/tree)	Wroots(ton/ha)
III	T2	0.7659	3.4054
III	T3	0.6001	3.2789
III	T4	1.4318	4.6023

C. CO2Fix model calibration

a. Biomass Module

For stem biomass (Figure 22), we used a wood density of 0.547 MgDM/m³ to reflect the mass of dry matter per unit volume. The initial carbon content was set at 0 MgC/ha across all components, establishing a baseline for the simulation. The Current Annual Increment (CAI) began at 0.17 m³/ha/year at 2 years to represent early growth phases and increased to 1 m³/ha/year by 12 years as the trees reached maturity, simulating the steady accumulation of stem biomass over time. These values, used for stems, were also applied to other components to maintain consistency across the model.

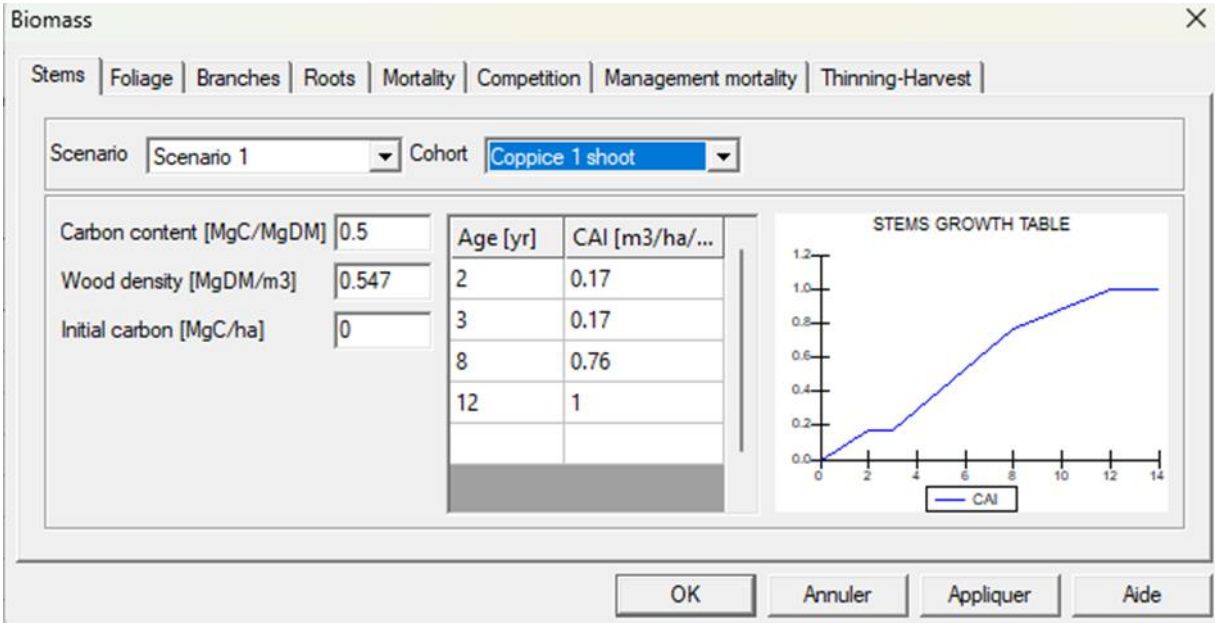


Figure 22 : Parameters of the CO2FIX biomass module: stem biomass growth and density dynamics (adapted from Schelhaas et al., 2004).

In regard to foliage biomass (Figure 23), a carbon content of 0.5 MgC/MgDM was set, representing the carbon proportion within the dry matter of leaves. The growth correction factor and turnover rate were both assigned a value of 1. Growth rates varied to reflect different stages of development: a rapid initial growth of 3 MgDM/ha/year at 1 year, tapering slightly to 2

MgDM/ha/year at 2 years, and stabilizing at 1.5 MgDM/ha/year by 4 and 12 years to model slower, steady growth as the canopy matures.

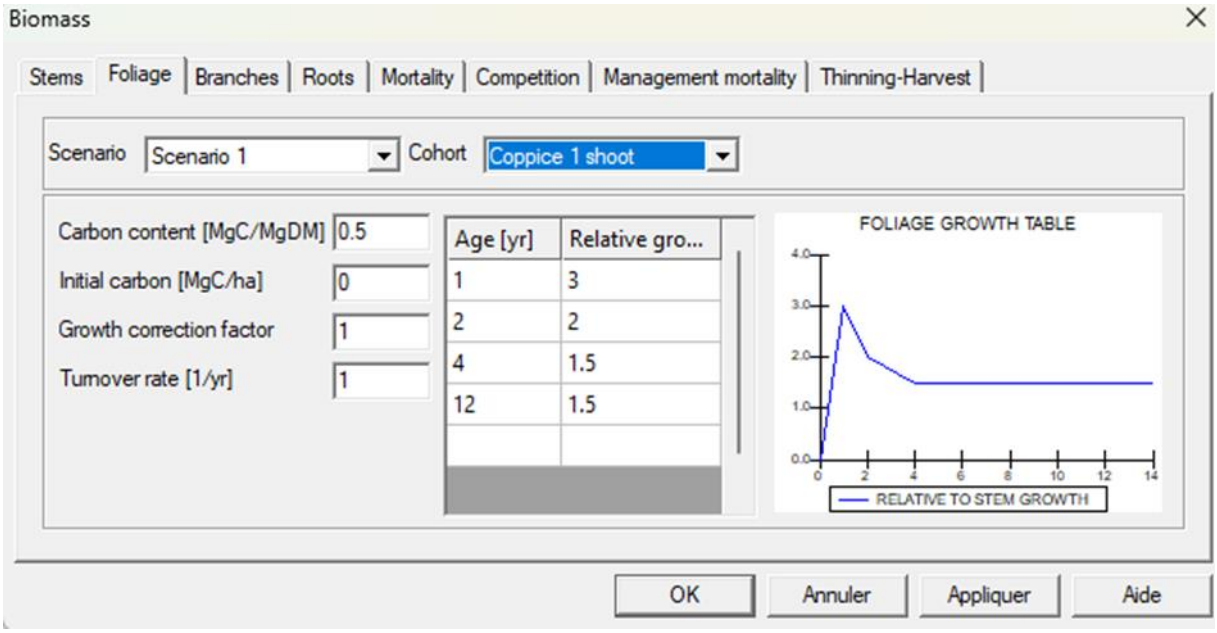


Figure 23 : Parameters of the CO2FIX biomass module: foliage growth and carbon content dynamic (adapted from Schelhaas et al., 2004)

A turnover rate of 0.021 was applied for branches (Figure 24), which represents the rate at which branch biomass is replaced or decomposed. Growth rates for branches were set at 0.5 at 1 year, 2.5 at 4 years, and 0.6 MgDM/ha/year at 12 years. These values capture the dynamic nature of branch growth, from initial rapid expansion to a more stable growth pattern in older trees.

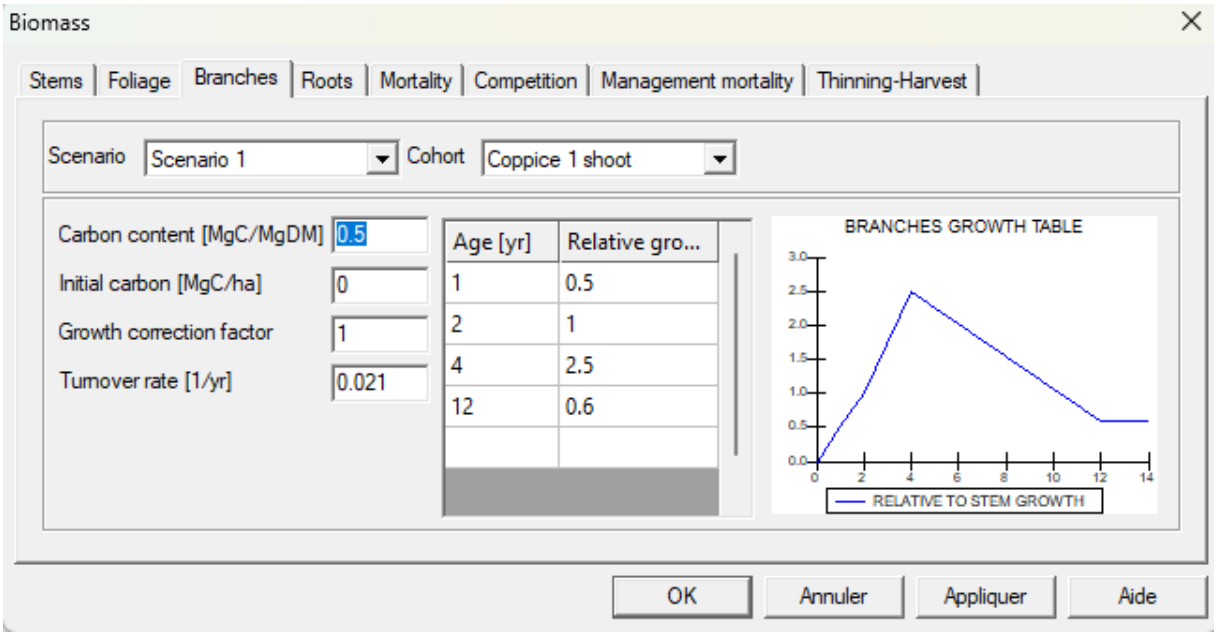


Figure 24 : Parameters of the CO2FIX biomass module: branches biomass and density dynamics (adapted from Schelhaas et al., 2004).

For root biomass (Figure 25), we assigned a turnover rate of 0.2, indicating a moderate rate of root biomass turnover. Growth rates were varied significantly: 1 at 1 year, 6.5 at both 2 and 4 years, and 5 Mg DM/ha/year at 12 years, reflecting the rapid initial growth and subsequent stabilization of root biomass over time. These parameters model the substantial role of roots in carbon storage and uptake.

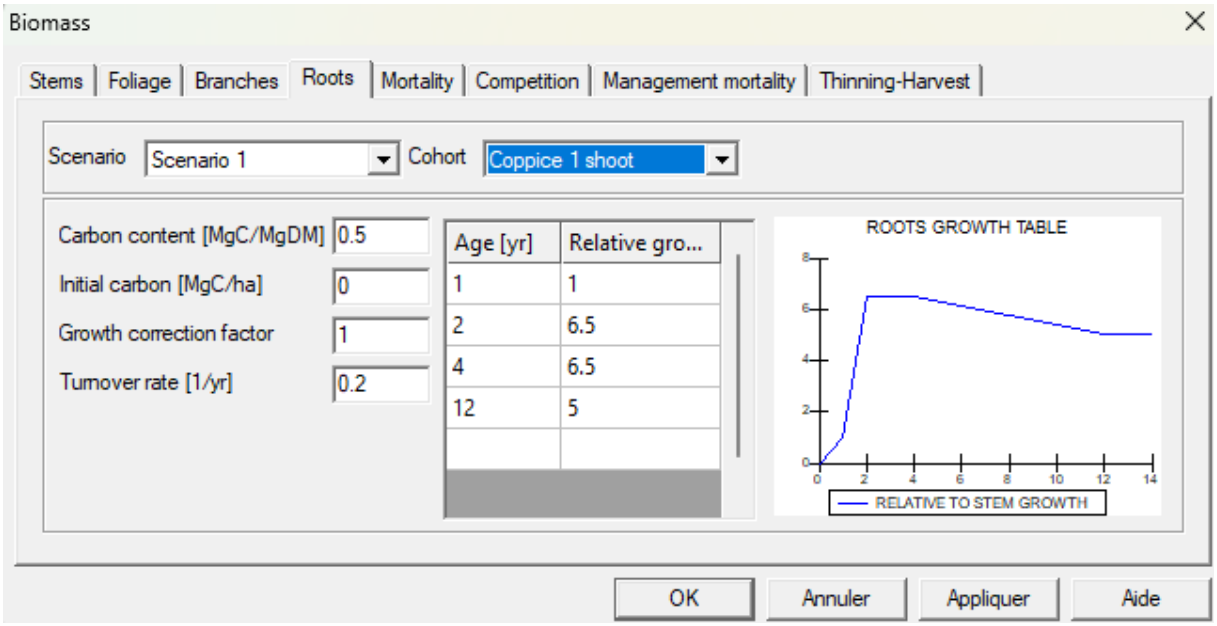


Figure 25 : Parameters of the CO2FIX biomass module: root biomass (adapted from Schelhaas et al., 2004).

b. Soil Module

We included environmental parameters to account for soil carbon dynamics (Figure 26) (IPMA, 2023). Degree days above 0 were set to 4619.2, representing the cumulative temperature above freezing which influences soil microbial activity and decomposition rates. Potential evapotranspiration during the growing season was set at 471.285 mm, indicating the amount of water evaporated and transpired by vegetation. Precipitation during the growing season was set at 246.1 mm, affecting soil moisture and carbon sequestration processes.

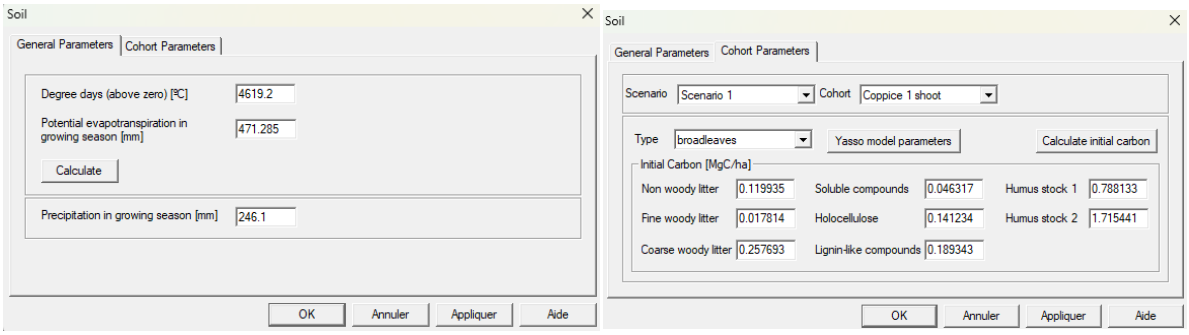


Figure 26 : Soil module parameters affecting carbon dynamics in the CO2Fix model (adapted from Schelhaas et al., 2004).

D. CO2Fix model validation

In our study, we compared the observed stem volume (V_observed) with the estimated values (V_CO2Fix) generated by the CO2Fix model for various treatments at ages 2, 4, and 12 years. The data was organized in a table and plotted to visualize stem volume (in m³/ha) over time (Table 11). The resulting graph (Figure 27) illustrates the curves for each treatment, enabling a comprehensive analysis of the CO2Fix model's performance across different scenarios.

Table 11 : Comparison of observed and estimated stem volume (Vobs vs. VestCO2Fix) at 2, 4, and 12 years (Author's own work).

	1 shoot		3 shoots		5 shoots		HF	
Age	Vobs (m3/ha)	VestCO2Fix (m3/ha)	Vobs (m3/ha)	VestCO2Fix (m3/ha)	Vobs (m3/ha)	VestCO2Fix (m3/ha)	Vobs (m3/ha)	VestCO2Fix (m3/ha)
2	0.269	0.26	0.840	0.75	0.824	0.75	0.960	0.15
4	0.613	0.71	1.857	1.89	1.940	1.98	1.131	0.6
12	6.666	6.69	11.550	11.70	10.693	10.84	11.761	11.81

HF: high-forest

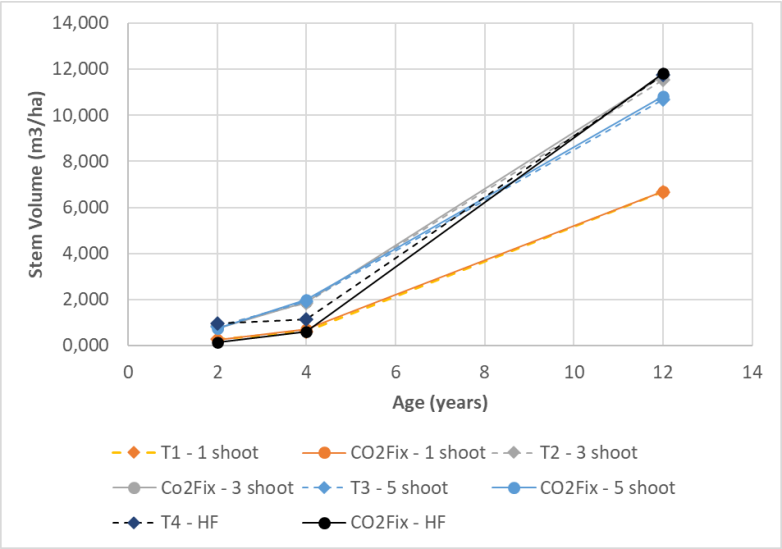


Figure 27 : Comparison of observed and CO2Fix modeled stem volumes over time (Author's own work).

From the graph (Figure 27), it is evident that the CO2Fix model generally predicts stem volume with reasonable accuracy, even though we can notice some deviations. For example, at 2 years, the model slightly underestimates stem volume for the T4 (high-forest) and T3 (5-shoot) treatments. By 4 years, the model's estimates are more closely aligned with observed values, though some minor discrepancies remain, particularly for the high forest treatment T4. At 12 years, the model's predictions for stem volume align closely with the observed values for the majority of treatments with only slight overestimations noted.

Overall, the graph illustrates that while the CO2Fix model provides a robust simulation of stem volume trends in chestnut coppices, further calibration may be necessary to refine its accuracy, especially at specific growth stages and for particular treatment types.

1. Biomass analysis by component and diameter

This section aims to assess the accuracy and reliability of the CO2Fix model in estimating biomass and carbon content in chestnut coppices. It serves as a foundation for understanding how well the model performs against actual measured data over various growth periods.

a. Stem biomass

Table 12 presents the stem biomass estimates generated by CO2Fix for various treatments over a 12-year period. The comparison of biomass produced in the trial, estimated by the selected equations for ages 2, 4, and 12 years, with the values obtained from the CO2Fix model for the same ages can be seen in Table 13 and Figure 28. This graphic aims to visualize the accumulation of stem biomass over time for the four different treatments (T1: 1 shoot, T2: 3 shoots, T3: 5 shoots, and T4: high forest). By showing the trends from 1 to 12 years, this graph

illustrates how varying shoot densities impact stem biomass production, which is an important factor in assessing the carbon sequestration potential of chestnut coppices. The graph presents the CO2Fix model estimates as curves, while the observed biomass values at specific time points (years 2, 4, and 12) are represented as symbols (Figure 28).

Table 12 : Stem biomass estimates by CO2Fix for different treatments over 12 years (Author's own work).

Treatment	1 shoot	3 shoots	5 shoots	HF
Age	Stem Biomass CO2Fix(Ton/ha)			
1	0.05	0.14	0.14	0.03
2	0.14	0.41	0.41	0.08
3	0.23	0.68	0.72	0.14
4	0.39	1.03	1.08	0.33
5	0.61	1.46	1.5	0.65
6	0.9	1.97	1.98	1.11
7	1.25	2.55	2.52	1.7
8	1.67	3.22	3.12	2.43
9	2.11	3.93	3.76	3.27
10	2.6	4.7	4.44	4.22
11	3.11	5.52	5.16	5.28
12	3.66	6.4	5.93	6.46

HF: high-forest

Table 13 : Observed stem biomass (Ton/ha) for different treatments at 2, 4, and 12 years (Author's own work).

Age (years)	T1-A	T2-B	T3-C	T4-D
2	0.1472	0.4595	0.4505	0.5249
4	0.3353	1.0157	1.0613	0.6185
12	3.6464	6.3176	5.8493	6.4332

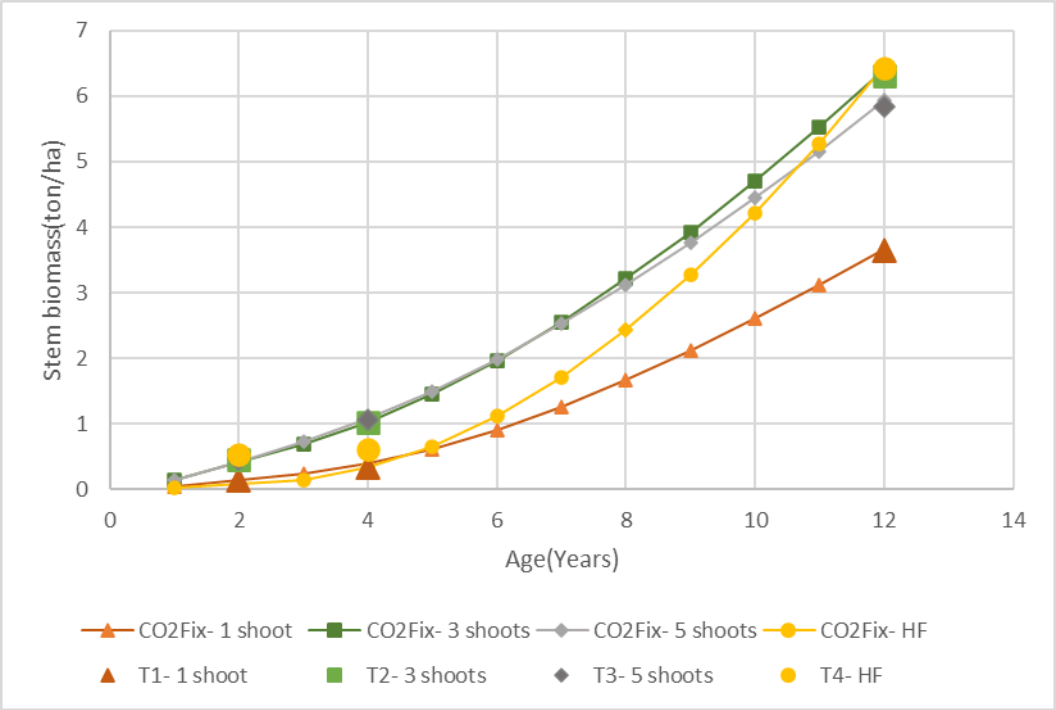


Figure 28 : Stem biomass over time for different treatments in chestnut coppices: comparing co2fix model estimates and observed values from years 1 to 12 (Author's own work).

From the graphic (Figure 28), we can see that the stem biomass increases gradually over time across all treatments, T4 (High Forest) shows the highest biomass accumulation from the start and maintains this lead, ending with approximately 6.46 Ton/ha of biomass at 12 years. However, due to the fact that this treatment was not converted to coppice, it exhibits different behavior compared to treatment T1. At 4 years, it shows lower biomass accumulation than treatments T2 and T3, but it gradually recovers, aligning with T2 by the age of 12. The treatments T2 (3 shoots) and T3 (5 shoots) display similar progression, with T2 slightly outperforming T3 by the end of the 12-years period. At 12 years, T2 reaches 6.4 Ton/ha, while T3 reaches 5.93 Ton/ha. T1 (1 shoot) consistently shows the lowest biomass accumulation, with 3.66 Ton/ha at year 12.

At 2 years, the observed values closely align with the CO2Fix predictions for T1 and T3, with minor variance. T2 is slightly overestimated by the model (0.41 vs. 0.460), while T4 is underestimated (0.08 vs. 0.525). By the 4th year, the model closely matches the observed values for all treatments, particularly T2 and T3. However, T4's observed value is still higher than the model prediction (0.619 *vs.* 0.33). This may be due to the fact that this treatment was not converted to coppice.

At 12 years, the CO2Fix predictions align well with the observed data across all treatments. The difference between the model and observed values is minimal, particularly for T1 and T4. For example, T1 is predicted to be 3.66 Ton/ha, closely matching the observed value of 3.65 Ton/ha, while T4 shows a similar alignment, with a predict value of 6.46 Ton/ha compared to an observed value of 6.43 Ton/ha.

The graphic (Figure 28) clearly shows how stem biomass evolves over time in relation to shoot density and treatment. T4 (high forest), which has only one stem, results in the highest stem biomass due to a longer period of biomass accumulation (19 years). In the juvenile phase, the number of stems appears to positively impact the amount of biomass produced and carbon stored compared to the high forest. However, this difference diminishes with age, as the mean annual increment in stem volume shows a declining trend in the coppice system, while it continues to increase in the high-forest system (Patrício & Nunes, 2024). According to the authors, the high-forest system typically exhibits lower height and diameter than the coppice system during the juvenile phase, especially in management models with similar objectives.

T1 (1 shoot) consistently shows the lowest stem biomass, which suggests that limiting shoot density reduces overall biomass accumulation and, consequently, carbon storage potential. T2 (3 shoots) and T3 (5 shoots) are the highest producers of biomass, with T2 demonstrating a slightly higher biomass yield at 12 years, indicating their greater capacity to produce biomass and sequester carbon during the juvenile phase. This observation underscores the idea that the differences between the two reflect the influence of shoot density on growth rates, as their curves begin to diverge at later stages.

To review and assess how accurate the CO2Fix model can predict biomass growth over time, the comparison between predicted model's results and observed data is important. Although there are some minor differences between 2 and 4 years, especially for treatment T4, the model still matches closely the field data at 12 years, which suggests that the model is well suited for long term projections of carbon sequestration and biomass prediction. The graphic effectively indicates the effects of shoot densities on the evolution of stem biomass and eventually carbon storage, which was clearly shown in treatments with higher shoot densities leading to more biomass accumulation.

b. Total above-ground biomass

In Table 14, the total aboveground biomass estimated by the CO2Fix model is presented, while in Table 15, the estimate of total aboveground biomass is shown using equations from the

literature, specifically from Menéndez-Miguélez et al. (2013), Cutini (2000), and Leonardi et al. (1996). This approach allowed for a comparison between the estimates obtained by the CO2Fix model and those derived from these models, with the aim of calibration and validation.

Table 14 : Total above-ground biomass estimates at 12 years for different treatments (Author's own work).

Treatment	1 shoot	3 shoot	5 shoot	HF
Age (years)	Total above-ground biomass CO2Fix(Ton/ha)			
1	0.11	0.34	0.34	0.07
2	0.44	1.29	1.29	0.26
3	0.67	1.97	2.12	0.39
4	1.29	3.24	3.39	1.24
5	2.09	4.71	4.82	2.49
6	3.04	6.31	6.3	4.04
7	4.08	7.98	7.81	5.86
8	5.18	9.69	9.32	7.85
9	6.21	11.31	10.76	9.86
10	7.19	12.85	12.1	11.9
11	8.1	14.29	13.35	13.88
12	8.94	15.61	14.5	15.79

Table 15 : Above ground biomass (ton/ha) at 12 years for different treatments based on equations of Menéndez-Miguélez et al. (2013), Cutini (2000), and Leonardi et al. (1996) (Author's own work).

Treatment/author	Menéndez-Miguélez et al. (2013)	Cutini (2000)	Leonardi et al. (1996)
T1	25.7825	12.1463	2.9787
T2	30.3898	12.8559	6.1713
T3	29.0112	13.0752	5.5469
T4	32.7947	11.6169	5.7998

The graph in Figure 29 illustrates the changes in total above-ground biomass over a 12-year period for four treatments (T1: 1 shoot, T2: 3 shoots, T3: 5 shoots, T4: high forest) based on the CO2Fix model. Additionally, the graph includes symbols representing the mean total above-ground biomass at 12 years for each treatment, as calculated by different authors: Cutini (2000), Leonardi et al. (1996), and Menéndez-Miguélez et al. (2013). The goal is to compare the CO2Fix model predictions with estimated values from different sources and evaluate the impact of shoot density on total biomass production and carbon sequestration potential.

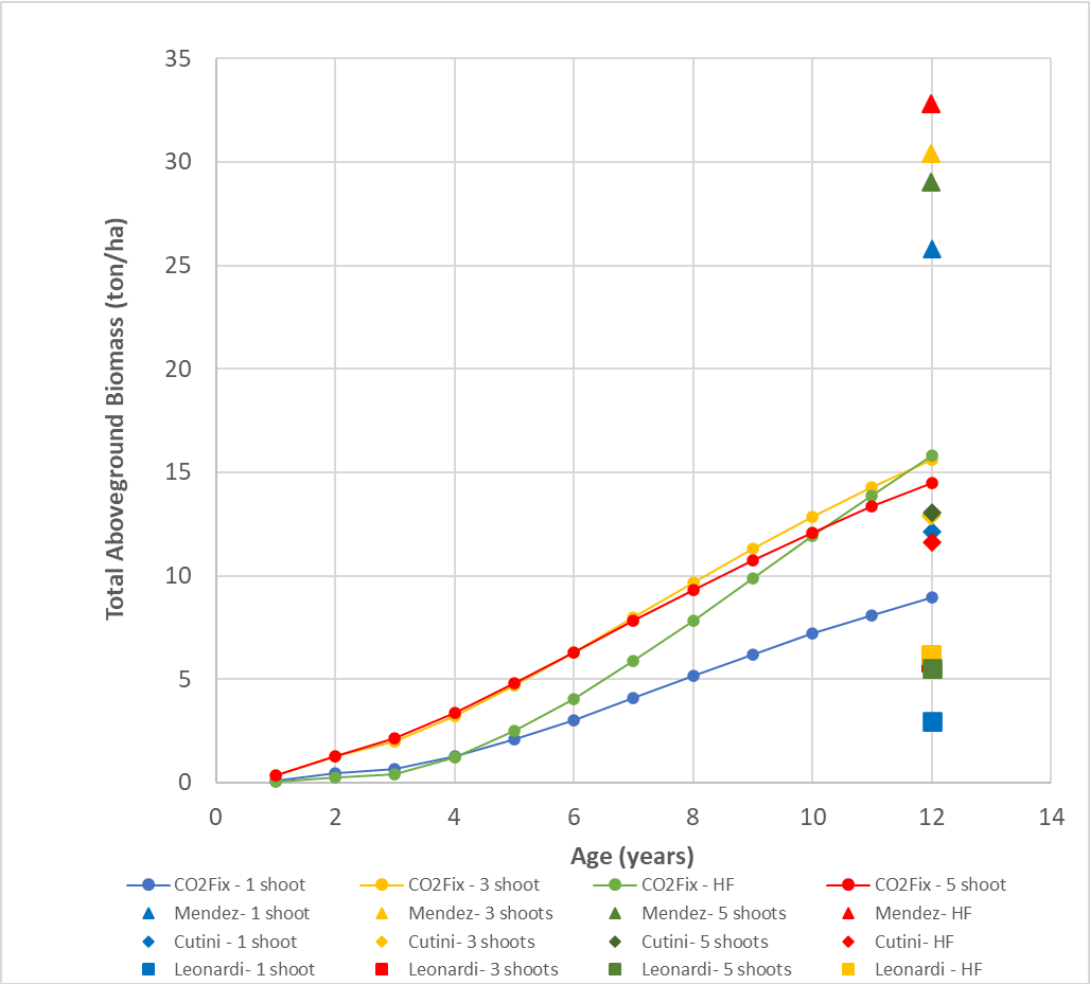


Figure 29 : Total above-ground biomass over 12 years for different treatments: co2fix model estimates vs. estimates by cutini, leonardi, and menéndez-migueléz (Author's own work).

Across all treatments, the total above-ground biomass increases steadily with age. T4 (high forest) shows the highest total biomass accumulation, reaching about 15.79 Ton/ha by 12 years, followed by T2 (3 shoots) at 15.61 Ton/ha, T3 (5 shoots) at 14.50 Ton/ha, and T1 (1 shoot) at 8.94 Ton/ha. Notably, the biomass production gap between T1 and the other treatments widens over time, indicating that lower shoot densities (T1) result in significantly lower total biomass, whereas T4 shows higher values because this treatment was not converted to coppice, as explained earlier.

For the T1 (1 shoot), the CO2Fix model predicts 8.94 Ton/ha of biomass, which is far lower than the estimate by Menéndez-Migueléz's equation (25.78 Ton/ha). However, Leonardi's equation presents an underestimated value (2.98 Ton/ha). Cutini's estimate (12.15 Ton/ha) is somewhat higher than the model's prediction. At T2 (3 shoots), the model estimates 15.61 Ton/ha of biomass, while the estimates from Menéndez (30.39 Ton/ha) are significantly higher. Leonardi's and Cutini's equations estimate lower biomass values at 6.17 Ton/ha and 12.86

Ton/ha, respectively. For the T3 (5 shoots), the CO2Fix model predicts 14.50 Ton/ha, again lower than Menéndez-Migueléz's estimate (29.01 Ton/ha) but higher than Leonardi's (5.55 Ton/ha) and Cutini's (13.08 Ton/ha). And for T4 (high forest), the CO2Fix model shows 15.79 Ton/ha, deviating from Leonardi's estimate (5.80 Ton/ha), but falling far short of Menéndez-Miguélez's (32.79 Ton/ha). Cutini's estimate of 11.62 Ton/ha is the closest to the CO2Fix estimate. As can be seen in the graph in Figure 29, Cutini's estimates are generally closer to the estimates obtained with the CO2Fix model. The estimates obtained with Menéndez-Miguélez's and Leonardi's equations diverge considerably, with Menéndez-Miguélez's being an overestimate and Leonardi's being an underestimate.

T1 (1 Shoot) exhibits the lowest total biomass production, which is expected, as lower shoot density limits growth potential. However, while the CO2Fix model predicts a low biomass value, the estimates from Menéndez-Migueléz's and Cutini's suggest much higher biomass accumulation for T1 than predicted by the CO2Fix model.

Ultimately, the results underline the importance of testing multiple approaches to estimate biomass and carbon sequestration potential, particularly when considering different management practices in chestnut coppices.

These results support our decision to use Cutini's equations for estimating stem, branch, and total biomass in our study, as they align closely with our data. For leaf biomass, we opted for estimates from Leonardi's, given their greater reliability for our work.

c. Above-ground biomass by component and as a function of diameter

Figures 30, 31, 32, and 33 present the biomass produced for the different shoot components: stems, branches, and leaves, categorized by diameter class for each treatment at 12 years of age. These histograms provide a comprehensive overview of the biomass distribution among the various shoot components. In this analysis, biomass values for stems and branches were estimated using Cutini's equations, while leaf biomass was calculated using Leonardi's equation as referred to in the methodology.

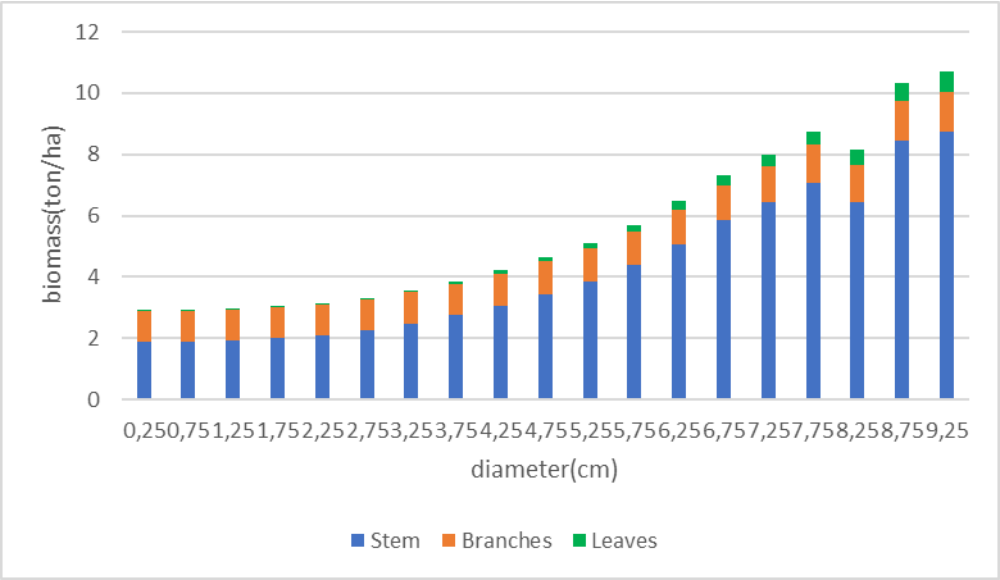


Figure 30 : Observed biomass (Ton/ha) by shoot component across diameter classes for T1 at 12 years (Author's own work).

As expected, in general biomass increases by diameter class, with the highest proportion found in the stems, followed by the branches, and finally the leaves. Specifically, stem biomass starts at 1.89 ton/ha for the 0.25 diameter class and rises to 8.74 ton/ha for the 9.25 class. Branch biomass follows a similar trend, beginning at 0.99 ton/ha at 0.25 diameter class and reaching 1.30 ton/ha at 9.25 diameter class. Leaf biomass, starting from a minimal 0.0002 ton/ha at 0.25 meters, increases to 0.66 ton/ha at 9.25 class, showing a smaller but noticeable rise in proportion with increasing diameter. The increasing trend in stem and branch biomass indicates that larger diameter shoots contribute more significantly to total biomass, enhancing carbon sequestration capacity. The relatively low leaf biomass reflects its minor contribution compared to stems and branches in total biomass.

The same tendency is observed for T2 as can be seen in Figure 31, where stem biomass rises from 1.89 ton/ha at the 0.25 diameter class to 9.25 ton/ha at the 8.25 diameter class. Branch biomass also increases from 0.99 ton/ha to 1.32 ton/ha over the same range. Leaf biomass remains relatively low but increases from 0.0002 ton/ha to 0.51 ton/ha, showing higher increase compared to T1. The results indicate that more shoots in T2 contribute more to stem and branch biomass per class, enhancing the overall carbon storage capacity. The slightly higher leaf biomass suggests an increment in the contribution of leaves to total biomass, though it remains less significant compared to stems and branches.

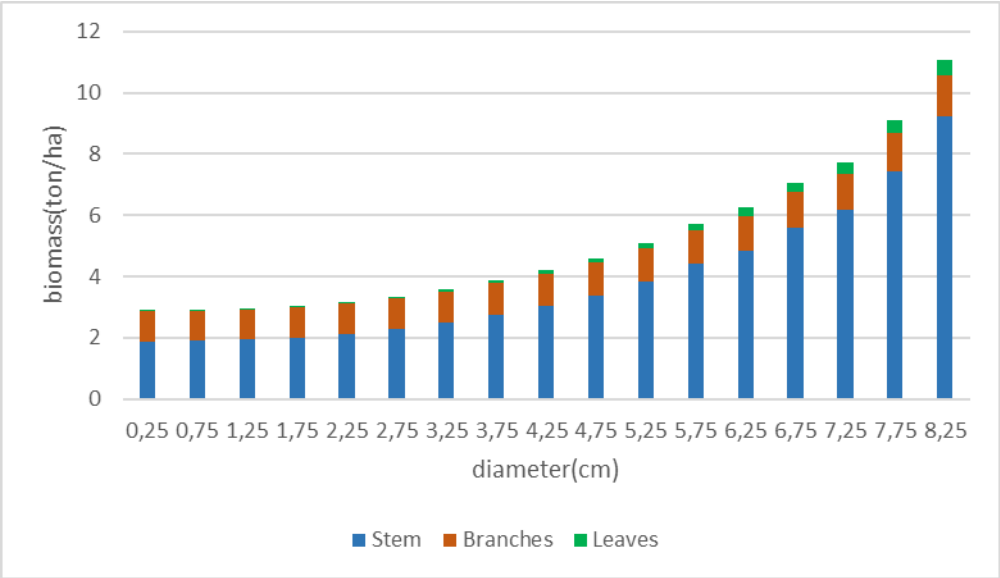


Figure 31 : Observed biomass (Ton/ha) by shoot component across diameter classes for T2 at 12 years (Author's own work).

The biomass distribution in T3 (Figure 32) is consistent with other treatments, with stem biomass increasing from 1.89 ton/ha of biomass at 0.25 diameter class to 8.73 ton/ha of biomass at 8.75 diameter class, and branch biomass rising from 0.99 ton/ha to 1.30 ton/ha. Leaf biomass shows a slight increase from 0.0002 ton/ha to 0.58 ton/ha. The substantial increase in stem and branch biomass in T3, due to the greater number of shoots, indicates effective biomass accumulation, contributing significantly to carbon sequestration. The increase in leaf biomass also points to a growing contribution of leaves to total biomass, but still less dominant than stems and branches.

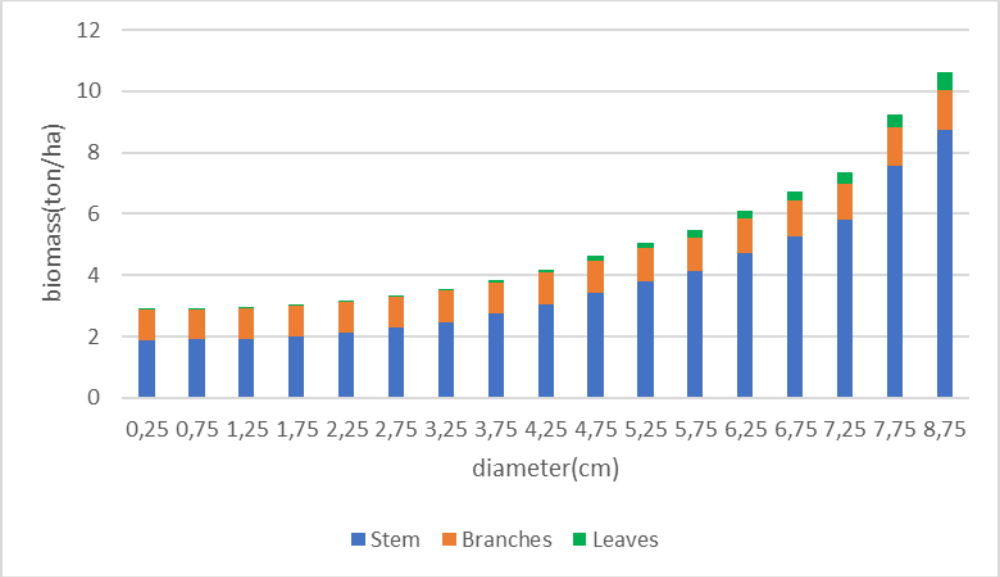


Figure 32 : Observed biomass (Ton/ha) by shoot component across diameter classes for T3 at 12 years (Author's own work).

Considering T4 as shown in Figure 33, the biomass values are notably higher, with stem biomass ranging from 1.89 ton/ha at 0.25 diameter class to 11.02 ton/ha at 9.25 diameter class. Branch biomass increases from 0.99 ton/ha to 1.40 ton/ha, while leaf biomass rises from 0.0002 ton/ha to 0.75 ton/ha. The large increase in both stem and branch biomass in T4 reflects a strong carbon sequestration capacity in larger diameter classes due to the older age of the aerial part, as it was not converted into coppice. The leaf biomass, although still the smallest component, shows the highest increase among treatments, suggesting a more substantial role of leaves in T4 compared to other treatments.

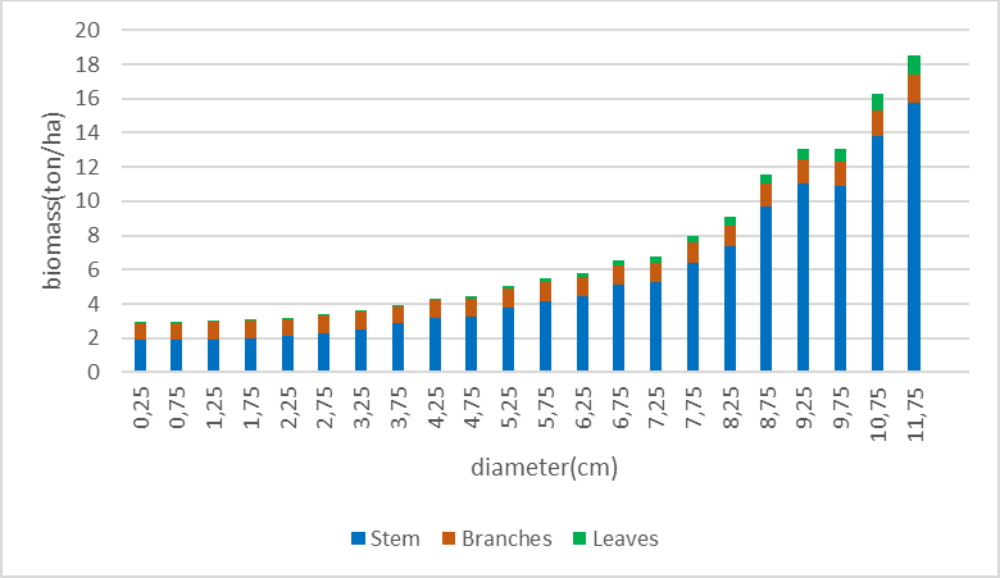


Figure 33 : Observed biomass (Ton/ha) by shoot component across diameter classes for T4 at 12 years (Author's own work).

Overall, the histograms highlight that larger diameter shoots/trees contribute the most to biomass, with stems and branches accounting for the majority of biomass across all treatments. The increase in biomass by diameter classes shows the importance of larger shoots in carbon sequestration. Stem account for the largest proportion of biomass, followed by branches, while leaves contribute the least. This distribution emphasizes the key role of stems and branches in carbon storage, suggesting that management practices aimed at enhancing their biomass could significantly improve carbon sequestration outcomes in chestnut coppices.

2. Comparative analysis of biomass estimates: CO2Fix *vs.* equations and observed data

a. Comparison of CO2Fix above ground and root biomass with Cutini's and Peinado's equations estimates

In assessing the CO2Fix model's performance, comparing above-ground and root biomass estimates to those obtained from Cutini's and Peinado's at 12 years provides valuable insights

into the model's accuracy and highlights the importance of considering both biomass tools in carbon sequestration assessments. Figure 34 presents this comparison for treatment T1, Figure 35 for T2, Figure 36 for T3, and Figure 37 for T4.

In treatment T1, the biomass estimated by Cutini's equation slightly overestimates the value compared to the CO2Fix model's estimate. A considerable discrepancy is observed in the root biomass estimates, as Peinado's model strongly underestimates values, relatively to the CO2Fix model and does not appear to be the most suitable for our conditions, despite being developed for the species.

For the root component, we should note, for all treatments, that there is a large discrepancy between the biomass and carbon estimates obtained using Peinado's equation, which, being the only available option, may not be the most suitable for our conditions, and the estimates obtained with the CO2Fix model. The lack of real data to validate this discrepancy prevents us from properly validating the model's results for this component. We assume that the values estimated by the CO2Fix model may overestimate the roots. However, the same methodology was used by Prado et al. (2016).

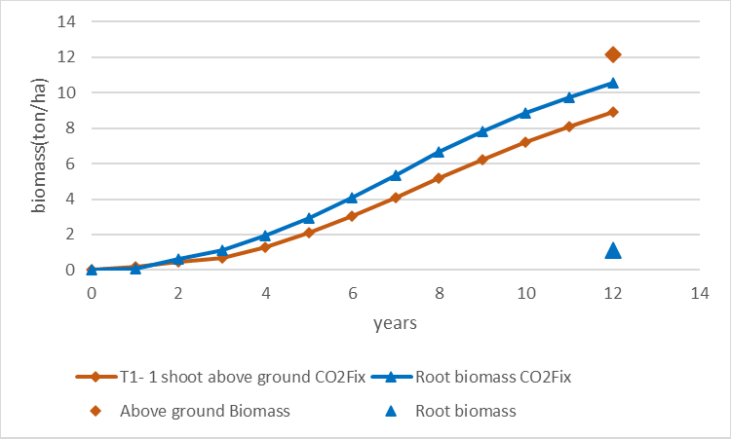


Figure 34 : Above-ground biomass (CO2Fix) compared to Cutini's equation estimates at 12 years and root biomass (CO2Fix) compared to Peinado's equation estimates at 12 years for T1 (Author's own work).

In treatment T2 shown in the Figure 35, the biomass estimated by Cutini's equation slightly underestimates the value compared to the CO2Fix model's estimate. However, a considerable discrepancy is also observed in the root biomass estimates relative to Peinado's equation.

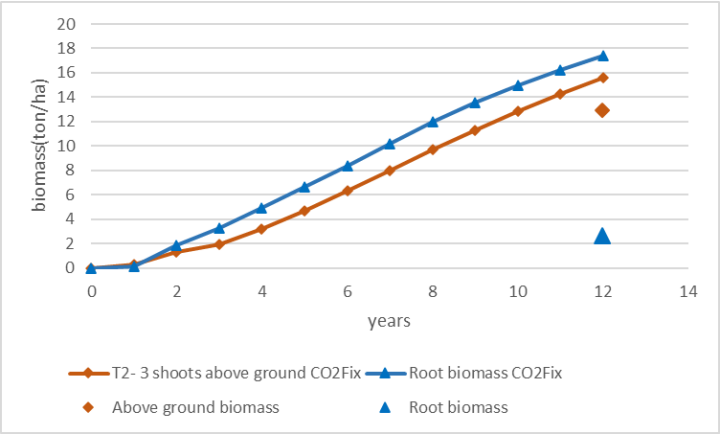


Figure 35 : Above-ground biomass (CO2Fix) compared to Cutini's equation estimates at 12 years and root biomass (CO2Fix) compared to Peinado's equation estimates at 12 years for T2 (Author's own work).

Considering the treatment T3 as illustrated in Figure 36, the biomass estimated by Cutini's equation slightly underestimates the value compared to the CO2Fix model's estimate, although it is very close to this estimated value. The same discrepancy observed in T2 is also found in the root biomass estimates relative to Peinado's equation.

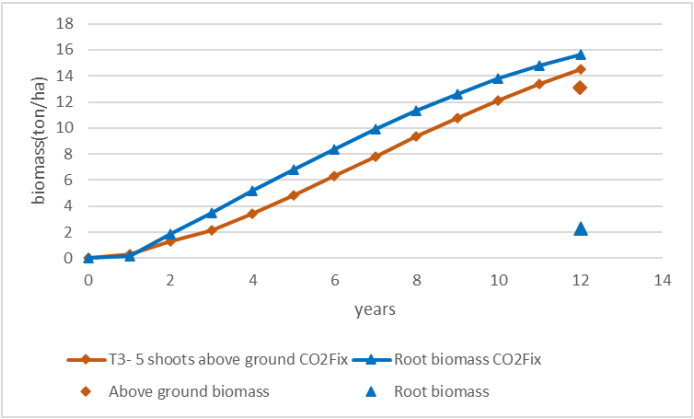


Figure 36 : Above-ground biomass (CO2Fix) compared to Cutini's equation estimates at 12 years and root biomass (CO2Fix) compared to Peinado's equation estimates at 12 years for T3 (Author's own work).

T4 exhibits the same behavior as T1 regarding root biomass (Figure 37); however, it diverges in the estimation of above-ground biomass compared to the CO2Fix model, showing a slight underestimation in this case.

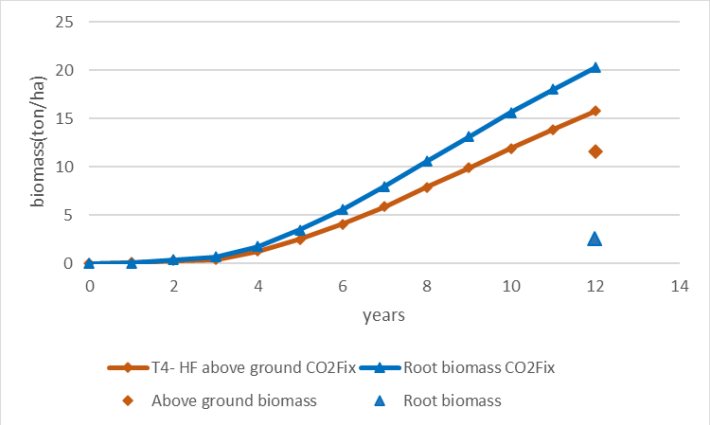


Figure 37 : Above-ground biomass (CO2Fix) compared to Cutini's equation estimates at 12 years and root biomass (CO2Fix) compared to Peinado's equation estimates at 12 years for T4 (Author's own work).

The CO2Fix model estimates for above-ground biomass show some deviations from the Cutini's estimation values. Specifically, for treatment T1, the model predicts 8.94 Ton/ha, which is considerably lower than Cutini's observed 12.15 Ton/ha. For treatment T2, the model's estimate of 15.61 Ton/ha is higher than Cutini's 12.86 Ton/ha. Similarly, treatment T3 shows a CO2Fix model estimate of 14.50 Ton/ha which is close to Cutini's 13.08 Ton/ha, while treatment T4 has a model estimate of 15.79 Ton/ha compared to Cutini's 11.62 Ton/ha. This pattern indicates that while the CO2Fix model captures the general trend of increasing biomass with treatment intensity, it tends to overestimate biomass for the majority of treatments. However, for the total biomass, this comparison has limitations regarding root biomass, as we do not have an equation to estimate the root component in chestnut coppices. Peinado's equation serves as an approximation only.

In general, CO2Fix model accurately reflects the trend of increasing root biomass, although it appears to overestimate this component. This overestimation indicates that the model may not fully capture the dynamics of root biomass, emphasizing the need for improved calibration to enhance accuracy.

The CO2Fix model generally aligns with trends in biomass accumulation in chestnut coppices under diverse management strategies, showing reasonable estimates of biomass and carbon stocks. However, variations observed between CO2Fix model estimates and those from equations for both above-ground and root biomass underline the model's current limitations, particularly regarding the root system for chestnut coppice. This highlights the importance of accurate biomass modeling in carbon sequestration assessments and the need for improved calibration. The overestimation of root biomass and the variable accuracy for above-ground biomass suggest that further refinement of CO2Fix model's calibration is necessary when

applied to chestnut coppices, primarily regarding the root component and the management of chestnut coppices with a lower number of shoots. Accurately modeling both above-ground and below-ground biomass components in chestnut coppices is crucial for a comprehensive understanding of carbon dynamics within these ecosystems.

b. Comparison between observed biomass and CO2Fix estimates for 2 and 4 years

This section of the analysis compares observed above-ground biomass values to CO2Fix model estimates for years 2 and 4 across all treatments using histograms as shown in Figure 38. These histograms visually represent the alignment between model estimates and observed data at early growth stages, helping assess the model's predictive accuracy. This comparison is essential for projecting long-term carbon sequestration potential.

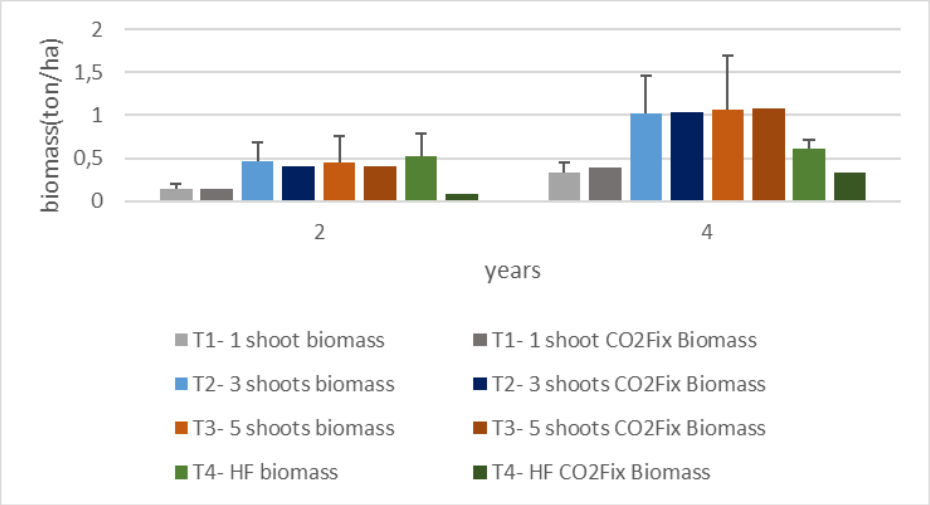


Figure 38 : Comparative analysis of observed above-ground biomass vs. CO2Fix model estimates at years 2 and 4 across treatments. (Author's own work).

At year 2, the observed biomass for T1 (0.147 Ton/ha) closely matched the CO2Fix estimate (0.14 Ton/ha). For T2 and T3, the model slightly underestimated biomass, while T4 showed a substantial underestimation (0.52 Ton/ha observed vs. 0.08 Ton/ha estimated). By year 4, T2 and T3 showed strong alignment between observed and model values, while T1 was slightly overestimated. For T4, the CO2Fix model continued to underestimate biomass (0.62 Ton/ha observed vs. 0.33 Ton/ha estimated).

The histograms for 2 and 4 years illustrate the strengths and limitations of the CO2Fix model in estimating early biomass accumulation. The model accurately predicts biomass for most treatments, particularly T2 and T3, but consistently underestimates biomass in Treatment 4 at both time points. Accurate early biomass predictions are crucial for assessing future carbon

storage potential. Variations in Treatment 4 may arise from factors not fully captured by the model, such as the fact that T4 has more above-ground biomass because it was not converted into coppice. Overall, the CO2Fix model demonstrates potential for simulating biomass and carbon accumulation.

c. Comparison between observed above-ground biomass and CO2Fix estimates for 12 years

In this section, we evaluate the CO2Fix model's performance at year 12 by comparing its above-ground biomass estimates with observed values across the four treatments (T1, T2, T3, and T4). The histograms generated for each treatment provide a visual representation of how accurately the model predicts long-term biomass accumulation, which is crucial for assessing carbon sequestration potential at this advanced growth stage as can be seen in Figure 39.

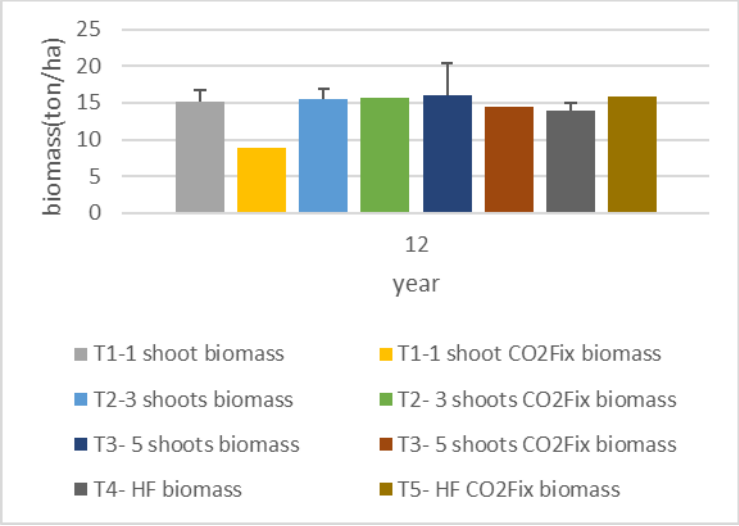


Figure 39 : Comparative analysis of observed aboveground biomass vs. CO2Fix Model estimates at 12 years across treatments. (Author's own work).

At 12 years, the observed biomass for T1 was 15.11 Ton/ha, while the CO2Fix model estimated 8.94 Ton/ha, indicating a considerable underestimation. In T2, the observed biomass was 15.58 Ton/ha, closely aligned with the model's estimate of 15.61 Ton/ha, showing high accuracy. For T3, the observed value was 15.98 Ton/ha, with the model estimating 14.50 Ton/ha, showing a slight underestimation. In T4, the observed biomass was 14.00 Ton/ha, and the model overestimated it at 15.79 Ton/ha. This suggests that the model faces challenges with lower shoot densities in the long term, possibly due to limitations in simulating growth dynamics under a more restrictive number of shoots.

Overall, the CO2Fix model provides a reliable estimate of above-ground biomass at year 12, but the accuracy varies depending on the treatment.

3. Carbon content analysis by component and diameter

a. Above-ground carbon content by component in function of diameter classes at 12 years

The histogram illustrates the percentage of total carbon stored in stems, branches, and leaves by diameter class at 12 years. It reveals how carbon allocation varies with tree size, which is crucial for understanding biomass growth patterns and carbon sequestration potential. By differentiating carbon distribution among the plant components, the graphic provides insights into carbon dynamics in chestnut coppice stands, informing forest management and optimizing carbon storage as illustrated in Figures 40 to 43.

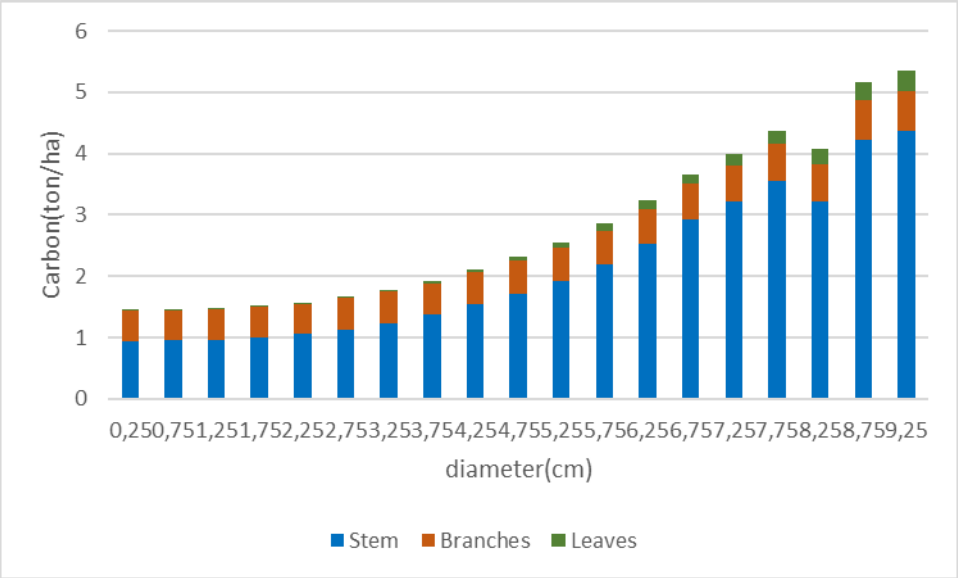


Figure 40 : Aboveground carbon allocation (Ton/ha) by diameter class for T1 at 12 years (Author's own work).

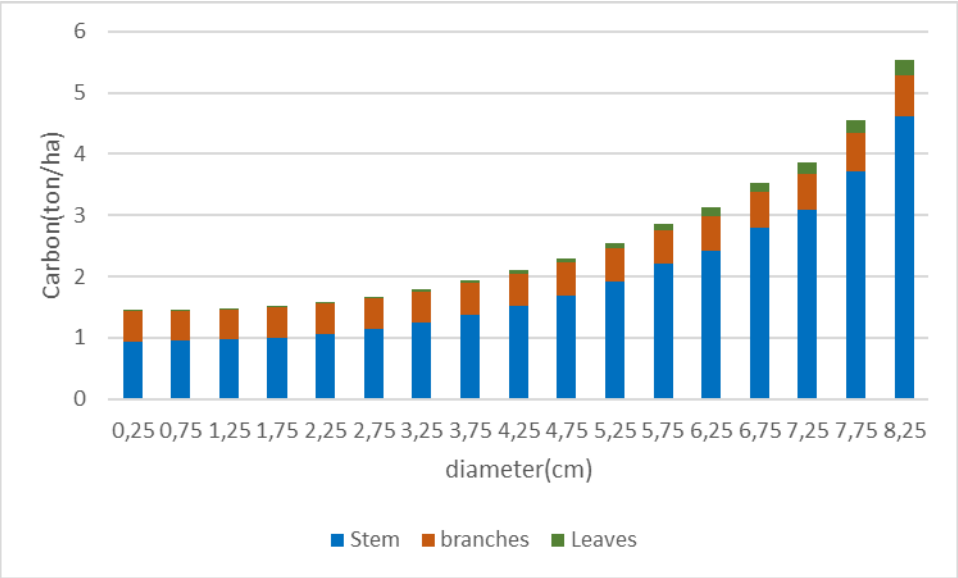


Figure 41 : Aboveground carbon allocation (Ton/ha) by diameter class for T2 at 12 years (Author's own work).

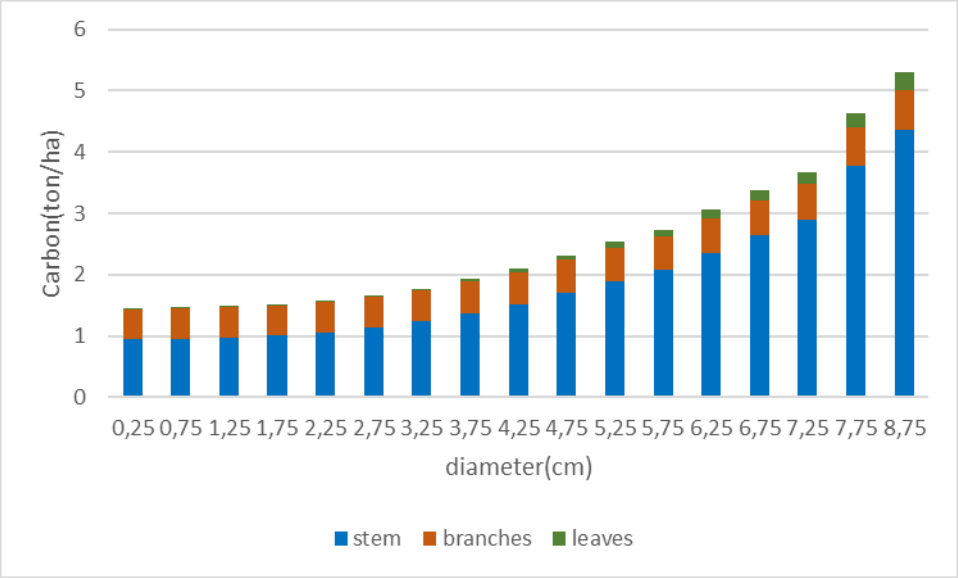


Figure 42 : Aboveground carbon allocation (Ton/ha) by diameter class for T3 at 12 years (Author's own work).

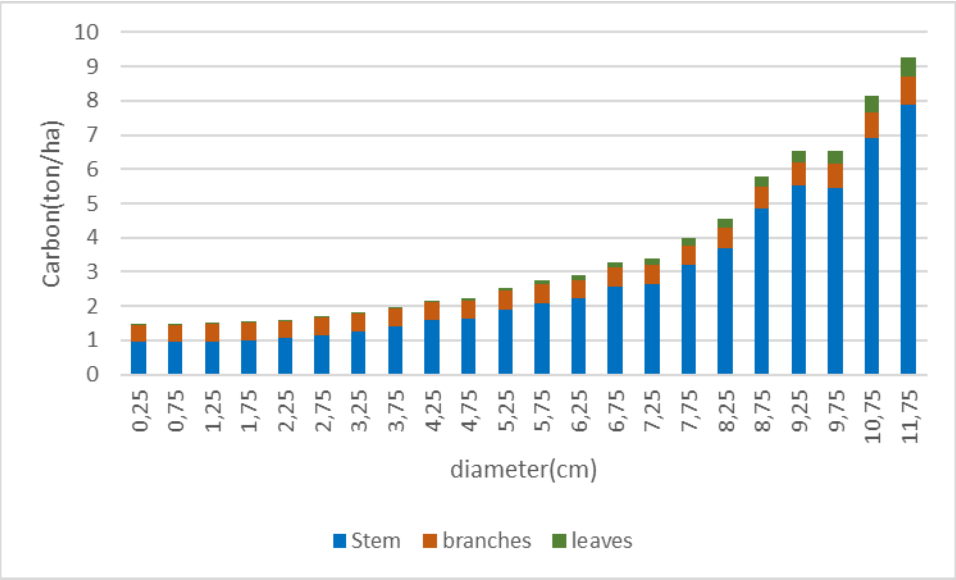


Figure 43 : Aboveground carbon allocation (Ton/ha) by diameter class for T4 at 12 years (Author's own work).

Across all treatments, stems store the most carbon due to their growth in diameter and biomass accumulation. Carbon in stems increases steadily from the smallest diameter class and peaks significantly in larger classes (e.g., 7.885 Ton/ha C in treatment T4 at the 9.25 cm class). Branch carbon storage also increases slightly with diameter, reaching 0.808 Ton/ha C in treatment T1's largest class, indicating a moderate contribution.

Leaves store the least carbon due to their lighter biomass, but leaf carbon increases with diameter, rising to 0.572 Ton/ha C in treatment T4 at the 9.25 cm class, highlighting their role in nutrient cycling.

Stem biomass is the most significant contributor to carbon sequestration across all treatments, indicating that management practices aimed at promoting stem growth, such as reducing shoot numbers, could enhance long-term carbon storage in chestnut coppices. While branches and leaves contribute less to carbon storage, their roles in nutrient cycling and understanding ecosystem productivity, particularly in early growth stages, are important and should not be overlooked.

b. Comparison between observed above-ground carbon content and CO2Fix estimates for 12 years

Figure 44 presents a comparison between observed aboveground carbon values and the CO2Fix model's carbon estimates for each treatment. The purpose of this comparison is to evaluate the accuracy of the model in estimating carbon sequestration potential across varying shoot

densities. For each treatment, the mean observed carbon values, along with their standard deviations (STD), are compared to the carbon estimates produced by the CO2Fix model.

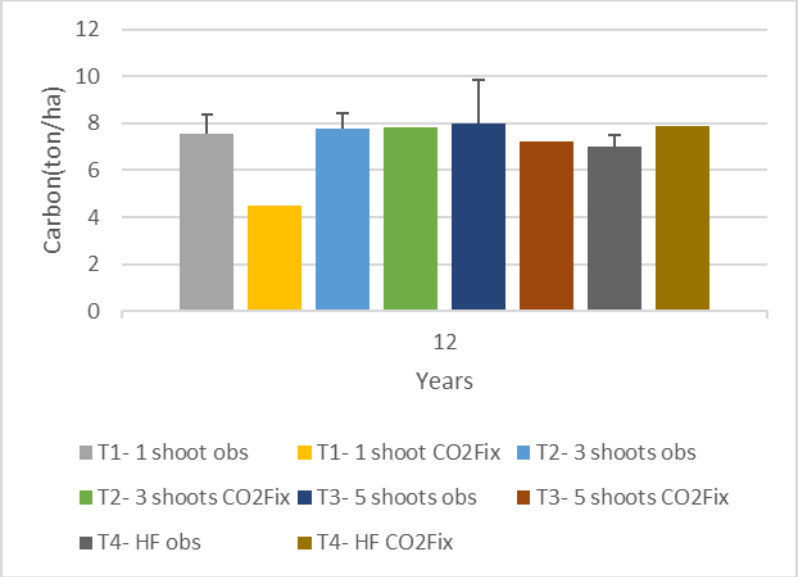


Figure 44 : Comparison of observed aboveground carbon and CO2Fix estimated carbon sequestration across different shoot densities for 12 years (Author's own work).

In T1 (1 shoot), the observed carbon was 7.56 Ton C/ha, while the CO2Fix model considerably underestimates this value, estimating only 4.47 Ton/ha. The observed difference was 3.09 Ton/ha, which corresponds to 49 % lower than the observed value. In T2 (3 shoots), the observed carbon was 7.79 Ton/ha, and the CO2Fix model closely aligns with this, estimating 7.81 Ton/ha, demonstrating minimal variation (+0.26%). For T3 (5 shoots), the observed carbon is 7.99 Ton/ha, and although the CO2Fix model slightly underestimates this value at 7.25 Ton/ha, the difference of 0.74 Ton/ha is relatively small (-9.26%). Lastly, in the T4 control, the observed carbon is 7.00 Ton/ha, while the CO2Fix model overestimates it at 7.90 Ton/ha, with a deviation of 0.9 Ton/ha (+12.86%).

This analysis shows that while the CO2Fix model provides accurate estimates for T2 and reasonable results for T3 and T4, it tends to underestimate carbon sequestration in T1, indicating that further calibration may be necessary to improve its performance for lower-density treatments.

c. Comparison between observed above-ground carbon content and CO2Fix estimates for 2 and 4 years

Figure 45 presents a comparison between the observed carbon values and the CO2Fix model's estimated carbon for each treatment (T1, T2, T3, and T4) at two different time points: 2 and 4

years. The purpose of this graph is to visually assess the accuracy of the CO2Fix model in estimating carbon sequestration across different shoot densities in chestnut coppice stands, using both the observed data and the CO2Fix model estimates for comparison.

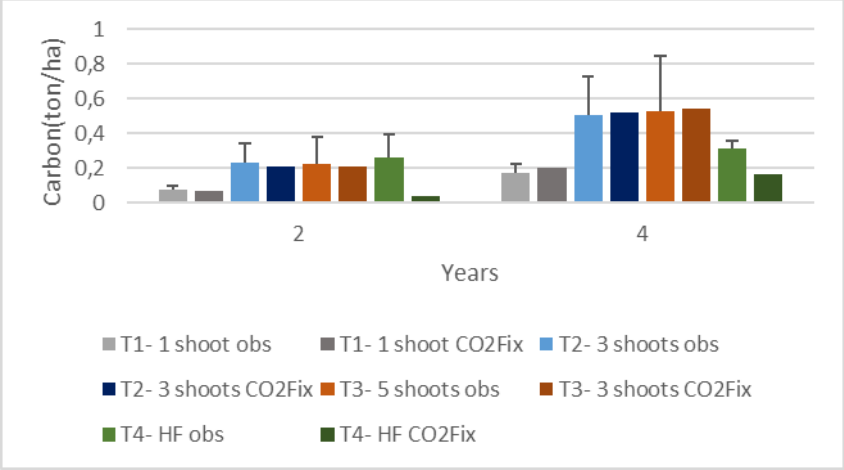


Figure 45 : Comparison of observed aboveground carbon and CO2Fix estimated carbon sequestration across different shoot densities for 2 and 4 years (Author's own work).

At 2 years, T1 (1 shoot) had an observed carbon of 0.0736 Ton/ha, closely matching the CO2Fix estimate of 0.07 Ton/ha. T2 (3 shoots) showed an observed carbon of 0.2298 Ton/ha, with CO2Fix estimating 0.21 Ton/ha (-8.6%). For T3 (5 shoots), the observed carbon was 0.2253 Ton/ha, and CO2Fix estimated 0.21 Ton/ha (-6.8%). In contrast, T4 (control) had a considerable underestimation, with an observed value of 0.2625 Ton/ha compared to CO2Fix's estimate of only 0.04 Ton/ha (-84.7%).

At 4 years, T1's observed carbon increased to 0.1677 Ton/ha, with CO2Fix estimating 0.2 Ton/ha (+19.3%). For T2, the observed carbon was 0.5079 Ton/ha, closely aligning with the CO2Fix estimate of 0.52 Ton/ha (+2.4%). In T3, the observed carbon was 0.5307 Ton/ha, with CO2Fix estimating 0.54 Ton/ha (+1.7%). For T4, the observed carbon was 0.3093 Ton/ha, while CO2Fix estimated 0.16 Ton/ha (-48.3%).

Overall, the histogram highlights that the CO2Fix model predictions are quite acceptable in treatments T1, T2, and T3 for both years, with minimal differences between observed and estimated carbon values. However, the model tends to significantly underestimate carbon for T4 at both 2 and 4 years, with the variation being more pronounced at 2 years. This suggests that the CO2Fix model is reasonably reliable for T1 and quite reliable for T2 and T3. Although, in general, we can consider the model reliable for most treatments, it may require further calibration for specific stand structures, particularly in low-density or control treatments such as T4.

E. Projections of chestnut coppice biomass production and carbon stock for a 42-year rotation period

Based on the yield tables from Bonet & Brizuela (1997), we simulated the long-term carbon evolution of chestnut coppice biomass production using the CO2Fix model for the four treatments in our study. This simulation, based on the data and insights provided by the reference, allowed us to project the carbon stock and biomass changes over a 42-year rotation period. Through this process, we aimed to assess the carbon sequestration potential of each treatment. However, it is important to note that the products module in CO2Fix was not explored due to certain limitations in our analysis.

Projected Biomass by component

Figure 46 presents the projected biomass distribution across various components (foliage, stem, branches, and roots) over time for treatments T1, T2, T3, and T4. This figure highlights how shoot density and management practices impact the accumulation of biomass in each tree component.

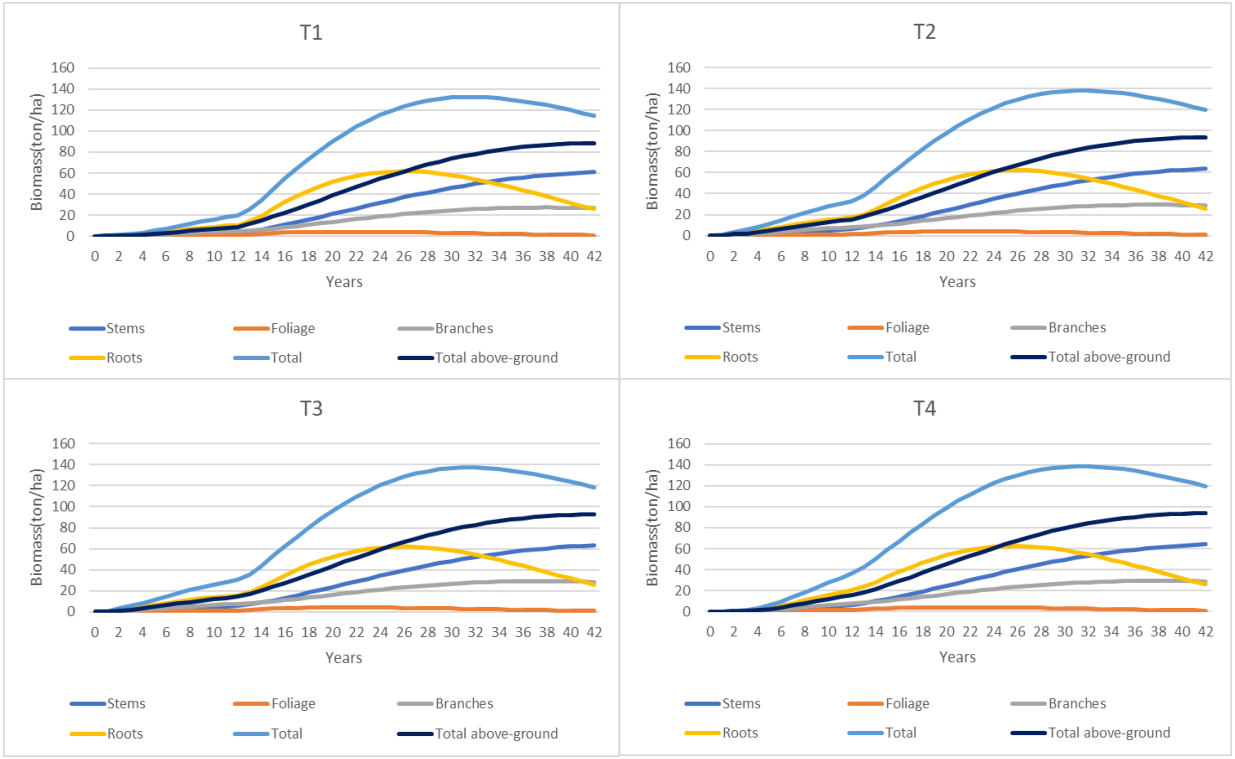


Figure 46 : Projected biomass distribution by component over 42 years for treatments T1, T2, T3 and T4 (Author's own work).

Biomass growth in T1 is gradual, with steady increases in all components. Stems show significant growth, reaching 60.87 tons/ha by year 42, while foliage contributes more in the

early years. The root and branch components increase but lag behind stem growth. Overall, T1 shows slower biomass accumulation compared to other treatments, with a total above-ground biomass of 88.49 tons/ha at year 42.

T2 (3 shoots) and T3 (5 shoots) both show strong biomass growth, with T2 reaching 63.94 tons/ha for stem biomass and a total above-ground biomass of 93.49 tons/ha at year 42. T3, while slightly behind in stem biomass at 63.36 tons/ha, has a total biomass of 118.49 tons/ha, just slightly lower than T2's 119.36 tons/ha. While T2 edges ahead in both total above-ground biomass and total biomass, the differences between the two treatments are small, highlighting their similar effectiveness in biomass production and carbon sequestration. Both treatments exhibit comparable trends in growth and carbon accumulation, indicating they are nearly equally capable of enhancing biomass and carbon storage over time.

The high-forest treatment (T4) shows biomass production at 42 years similar to treatments T2 and T3, with stems reaching 64.3 tons/ha. It is worth noting that the above-ground biomass corresponds to a growth period longer than the other treatments. By year 42, the total above-ground biomass reaches 93.77 tons/ha, similar to T2 and T3 but with a slower growth pattern. This treatment offers a more conservative and sustainable growth trajectory, although it results in lower biomass production in the early years.

T1 shows lower biomass production compared to T2 and T3, which have similar productions, with T2 slightly outperforming T3. T4 behaves slightly differently, reaching similar biomass values at the end of the rotation (above-ground biomass at 49 years, the same age as the root coppice in all treatments). T2 and T3 are the most effective for biomass production, while T4 offers higher biomass production than T1 with the same number of shoots. The maximum total biomass production is reached at 30-34 years, starting to decline from this age, although for above-ground biomass this trend occurs later. To maximize biomass production, harvesting should occur during this time period.

Projected Carbon content by component

Figure 47 illustrates the corresponding carbon content by component (foliage, stem, branches, roots, soil, total carbon, and total above-ground carbon) over the same 42-year period. These projections provide a comprehensive view of carbon sequestration across treatments, showing the contributions of different tree parts and soil to overall carbon storage.

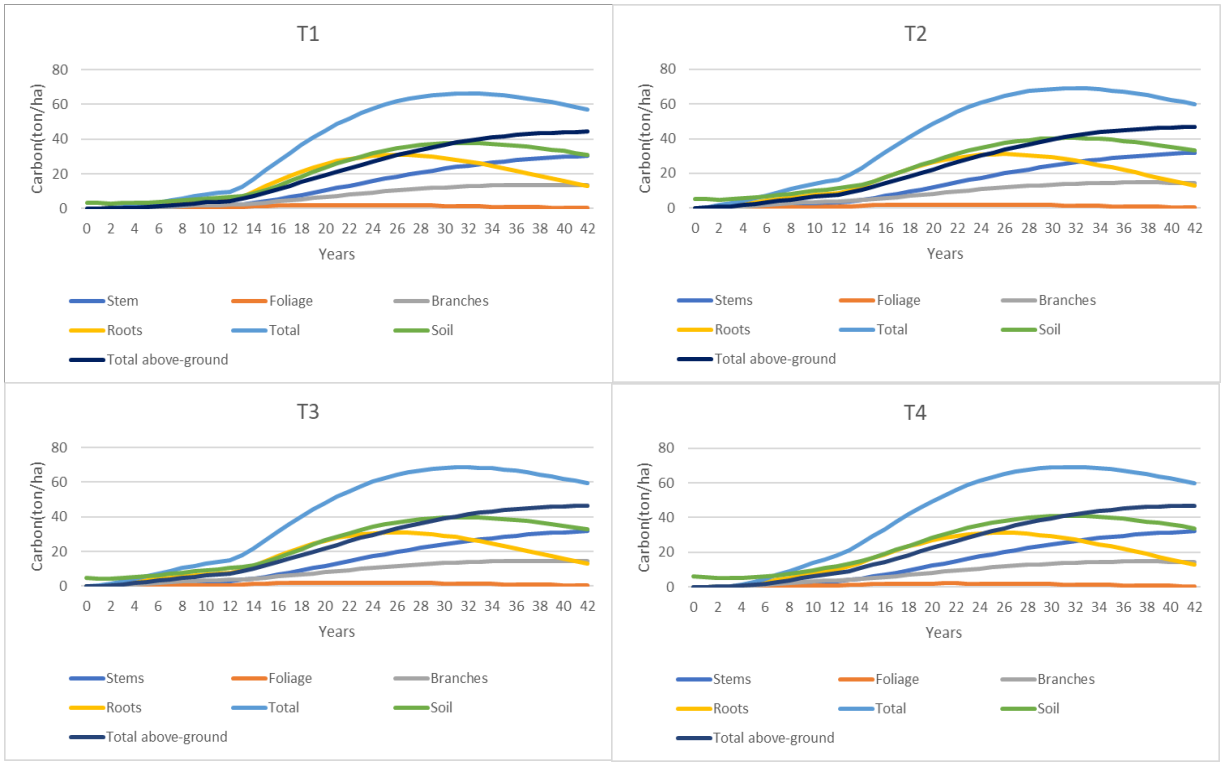


Figure 47 : Projected carbon content by component over 42 years for treatments T1, T2, T3 and T4 (Author's own work).

The evolution of carbon stocks over the 42 years for all treatments followed a similar overall trend, with carbon accumulation increasing steadily. Based on the data, T2 (3 shoots) and T3 (5 shoots) exhibited the highest carbon stocks, particularly in above-ground components, while T1 (1 shoot) and T4 (high forest) showed comparatively slower accumulation rates over time.

In T1, total carbon stocks remained modest, with low sequestration in the early years and a more noticeable increase after year 15, primarily in stems and foliage. After year 30, carbon stocks began to stabilize, and by year 35, a slight decline was observed, reaching approximately 57.18 tons/ha by year 42. T1 had the lowest total carbon among all treatments, reflecting its reduced number of shoots and consequently lower carbon accumulation over time.

In T2 (3 shoots) and T3 (5 shoots), total carbon sequestration was much higher, with both treatments showing significant increases in stems, roots, and foliage. T2 reached 68.79 tons/ha by year 30, stabilizing at 69.05 tons/ha by year 42. T3 had a similar growth pattern but experienced a minor decline in soil and root carbon, ending at 59.24 tons/ha by year 42. Both treatments showed plateauing between years 30-34, reflecting a maturing system with stabilized carbon dynamics. After this period, the total carbon sequestration capacity of the coppice began to decrease, although for above-ground carbon, this trend occurs later.

The high-forest treatment (T4) showed a slower, more gradual increase in carbon stocks. Early increases were slight, with more notable growth after year 10. By year 30, total carbon began to stabilize and remained steady for several years before slightly decreasing, reaching about 59.83 tons/ha by year 42. Although the total carbon in T4 increased gradually, it remained lower than in T2 and T3throughout the rotation but recovered towards the end, reflecting the conservative growth patterns typical of a high-forest system.

Soil carbon accumulation followed a similar trend across treatments, with T2 and T3 reaching around 40.19 and 39.58 tons/ha by year 42, respectively. T4 showed a more gradual increase, reaching 33.88 tons/ha, while T1 had the lowest soil carbon accumulation at 31.1 tons/ha. Based on the data, T2 and T3 exhibited slightly higher soil carbon levels compared to T1 and T4 throughout the rotation period.

Above-ground carbon in T2 and T3 made the largest contribution to the total carbon stocks since the accumulation of biomass in stems, roots, and foliage was most pronounced.

Overall, T2 and T3 were the most effective treatments for carbon sequestration, with T2 slightly outperforming T3. The differences in carbon accumulation between T1 and T4 were more gradual, reflecting the lower intensity of growth and carbon storage in these treatments. The results underscore the importance of shoot density in enhancing carbon sequestration, with higher shoot densities leading to more significant carbon storage over the long term.

V. Conclusions

The results of this trial underscore the importance of shoot density in driving biomass accumulation and carbon sequestration in chestnut coppices over a 42-year period. Treatments with higher shoot densities, specifically T2 (3 shoots) and T3 (5 shoots), showed the strongest biomass accumulation and highest carbon storage potential, particularly in stems, roots, and above-ground biomass. By year 42, total carbon content reached 57.18 tons/ha for T1, 69.05 tons/ha for T2, 59.24 tons/ha for T3, and 59.83 tons/ha for T4, illustrating the effectiveness of higher-density treatments in carbon sequestration.

While both T2 and T3 demonstrated strong biomass and carbon storage potential, T2 exhibited an advantage due to its larger-diameter shoots, which provide high-caliber timber products with valuable characteristics for long-term carbon storage. The robust structure and durability of timber from T2's 3-shoot treatment make it especially suitable for producing long-

lasting products that can sequester carbon over extended periods, thus offering greater versatility in both commercial value and ecological impact compared to T3's 5-shoot treatment.

In contrast, T1 (1 shoot) displayed slower biomass accumulation and lower total carbon stocks, but it could be a possibility when the aim is to produce more larger stems, whose wood can be incorporated into longer-lasting products, thus compensating environmentally. The high-forest treatment (T4) demonstrated a balanced growth pattern with steady biomass and carbon sequestration, achieving similar total carbon stocks to T2 and T3 by year 42, though its growth trajectory was more gradual. The CO2Fix model proved reliable for predicting biomass and carbon dynamics in treatments T1, T2, and T3, though it underestimated carbon stocks in T4, particularly in the early years, indicating a need for further calibration, especially for root component.

It is important to note that the biomass and carbon simulations over the 42-year rotation period by components provide valuable insights into the potential contribution of chestnut coppices under various silvicultural practices in the Mogadouro region. However, the simulations for root and soil components showed some inconsistencies that could be resolved with new local field data to better calibrate and validate the model in these areas. In contrast, the simulations for above-ground biomass and carbon appeared realistic, especially for treatments with a higher number of shoots per stool.

Overall, the findings highlight that higher shoot densities (T2 and T3) are most effective for optimizing carbon sequestration, while T4 offers a sustainable, long-term growth trajectory. These results support the role of management practices like thinning and adjusting rotation cycles to enhance biomass production, improve timber quality, and optimize carbon storage. They also reinforce the potential of chestnut coppices for contributing to climate change mitigation through well-planned silvicultural approaches, which improve carbon dynamics and promote sustainable forestry practices.

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