Life Cycle Assessment and climate effectiveness of Afforestation and Reforestation

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Abstract

Afforestation and reforestation (AR) is recognised as a key nature-based solution for carbon dioxide removal (CDR) in Europe. This study evaluates the climate performance of AR through a dynamic life cycle assessment (DLCA) approach, combining forest CO_2 sequestration estimates from the CO2FIX model and project related greenhouse gas (GHG) emissions modelling in Brightway25. Ireland is used as the case study for this analysis, with the framework designed to be extendable to the wider European context. Three forest management scenarios were developed, ranging from no management to intensive management, to assess their long-term impacts over a 100-year time horizon. Results show that, under conservative assumptions of 3.75 Mha available for AR, Ireland's technical potential ranges from -2.45 Gt CO_2-eq to -4.82 Gt CO_2-eq over 100 years. Project-related emissions from establishment, maintenance, and harvesting account for less than 2% of total impacts, with forest growth dynamics, management intensity, and biomass use for energy substitution identified as the main drivers of net climate benefit. While the results confirm AR's potential contribution to Ireland's and Europe's CDR targets, they also highlight uncertainties related to future climate conditions, disturbance risks, and the evolution of energy system emission factors. The proposed framework can be replicated for other countries to support informed decision-making on AR deployment strategies.

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1. Introduction

1.1 The role of carbon dioxide removal (CDR) in achieving climate targets

According to the latest IPCC report, the imperative to mitigate greenhouse gas emissions and limit global warming to 1.5 degrees Celsius above pre-industrial levels has become increasingly urgent. Staying under this mean temperature (and even under 2 degrees warming) will be decided by our actions during the next decades (Masson-Delmotte et al., 2021).

In this mindset, not only is it important to observe a rapid decrease in global emissions, it is necessary to deploy carbon dioxide removal (CDR) methods at a large scale to offset the emissions from hard-to-abate sectors (such as aviation, cement, and agriculture) (Terlouw et al., 2021). Even under strong mitigation pathways, several hundred gigatonnes of CO_2 must be removed from the atmosphere by 2100 to stabilize global temperatures and compensate for historical and future overshoot (IPCC, 2022; Cobo et al., 2022).

The IPCC stresses that CDR is not a substitute for deep emissions cuts but a critical complement to achieve net-zero and eventually net-negative emissions during the second half of the century (IPCC, 2022). However, delaying emissions reductions increases reliance on CDR later and raises the risk of overshooting temperature targets, along with the potential for irreversible environmental damage (IPCC, 2023).

1.2 Afforestation and Reforestation (AR) as a CDR

Afforestation and Reforestation stands out as a technically mature and cost-effective approach with significant mitigation potential.

In this thesis, the term *afforestation and reforestation* is used broadly to refer to the planting of forests in areas where forests can naturally grow (ecologically suitable areas). This includes both land that was recently deforested (*reforestation*) and land that has been without forest cover for a longer period (*afforestation*). While the distinction between the two is sometimes emphasized in the literature, both are treated together in this study, as the focus lies on the overall potential of forest planting to sequester carbon. For conciseness, afforestation and reforestation will hereafter be referred to as "AR".

According to the IPCC (2018), most 1.5 °C pathways rely on the expansion of forest sinks. AR is also recognized as one of the most scalable nature-based solutions, with the potential to contribute meaningfully to climate goals while delivering important co-benefits for ecosystems and communities (Doelman et al., 2020; Windisch et al., 2021; Griscom et al., 2017). In addition to sequestering atmospheric CO_2, well-designed AR projects can enhance biodiversity, improve water and air quality, support soil productivity, and create economic opportunities (Smith et al., 2019; Pan, 2024).

Despite these benefits, the real-world climate effectiveness of AR depends on many site-specific and methodological factors, which require closer examination.

1.3 Key challenges and knowledge gaps in AR

Despite its strong potential, the climate effectiveness of AR remains subject to several important uncertainties. One major concern is permanence: carbon stored in biomass is vulnerable to reversal through natural disturbances such as wildfires, pests, or disease outbreaks, particularly under changing climate conditions (Kilpeläinen et al., 2022; Pan et al., 2024). Moreover, the rate and magnitude of carbon sequestration vary widely depending on species, site conditions, and management practices, making outcomes highly location- and time-dependent (Smith et al., 2019; Terlouw et al., 2021). Another limitation lies in the methods used to assess climate impacts. While GHG inventories report overall carbon flows, they often exclude emissions associated with activities before and after forest growth, such as site preparation, transport, and the fate of harvested wood. Life Cycle Assessment (LCA) offers a more comprehensive evaluation by accounting for all life stages of an AR system, including emissions from site preparation, transport, and management (Larrey-Lassalle et al., 2022; IPCC, 2022). However, many LCA studies fail to incorporate temporal dynamics, such as time lags in carbon uptake or delayed emissions from harvested wood, which can bias climate benefit estimates (Levasseur et al., 2010; Terlouw et al., 2021). These gaps highlight the need for a more detailed, spatially and temporally explicit assessment of AR's real contribution to climate mitigation.

1.4 Objective, research question, and thesis outline

AR is widely recognized as a scalable and cost-effective carbon dioxide removal (CDR) strategy. However, estimating and comparing the actual climate effectiveness remains challenging due to variations in project design, regional conditions, and assessment methods. To support more consistent evaluation of AR across different contexts, this study develops a flexible methodological framework that can be applied to individual, regional, or national level projects. The goal is to enable clearer comparison of outcomes and help identify where AR can be most effective as a climate strategy.

The main research question guiding this thesis is:

How effective is afforestation and reforestation as a carbon dioxide removal strategy in Europe when evaluated using a life cycle approach?

To guide the analysis, this thesis is structured around the following sub-questions:

1. **Which regions in Europe offer the highest potential for AR implementation?**

2. **How much carbon can be sequestered over time through AR, considering species and management regimes?**

3. **What are the life cycle emissions associated with establishing and managing AR projects?**

4. **Which parameters have the greatest influence on the net climate benefit of AR?**

These questions are addressed in the following chapters, through spatial mapping, forest growth modelling, life cycle assessment, and sensitivity analysis.

The thesis is structured as follows. Chapter 2 presents a review of carbon dioxide removal (CDR) methods, with a focus on afforestation and reforestation and the use of life cycle assessment (LCA) to evaluate their climate impacts. Chapter 3 describes the methodology, including spatial mapping, the forest growth model (CO2FIX), the LCA model (Brightway25), and the case study in Ireland. Chapter 4 presents the results for AR potential, biomass growth, emissions, and the sensitivity analysis. Chapter 5 discusses the main findings, limitations, and broader implications. Chapter 6 concludes with a summary and outlook for future research.

2. Literature review

2.1. Overview of carbon dioxide removal (CDR)

2.1.1 Definition and role of CDR in climate mitigation

Carbon dioxide removal (CDR) refers to *the anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products* (IPCC, 2022, p. 114). These methods are not substitutes for emissions reductions but are necessary complements to help balance residual emissions from hard-to-abate sectors, compensate for historical emissions, or face a potential overshoot of the temperature goals (IPCC, 2022). Most scenarios in the IPCC Special Report (IPCC, 2018) rely on CDR to stay within 2 degrees Celsius of warming, and even more so to limit warming to 1.5 degrees Celsius (Terlouw et al., 2021)

The term Negative Emissions Technologies (NETs) is often used as a synonym of CDR but technically refers to technology-based methods that achieve net-negative emissions, such as direct air carbon capture and storage (DACCS) or bioenergy with carbon capture and storage (BECCS). CDR, as defined by the IPCC, has a broader scope and includes both engineered and nature-based methods such as afforestation, reforestation, soil carbon sequestration, and peatland restoration (IPCC, 2022).

2.1.2 Main categories of CDR approaches

CDR methods can be grouped into three categories:

- **Biological methods** rely on enhancing natural carbon sinks through processes like afforestation, reforestation, soil carbon sequestration, biochar application, or wetland restoration. These are generally low-cost, offer multiple co-benefits, and are already partially used in many regions.

- **Technological methods** include BECCS and DACCS, which capture carbon from biomass combustion or directly from the air and store it underground. These options offer a higher permanence but are costly, energy-intensive, and infrastructure-dependent.

- **Geochemical methods**, such as enhanced weathering, involve accelerating natural mineral reactions to sequester carbon in stable forms. These are still in early research and development phases and may require significant material and energy inputs.

2.1.3 Common challenges across CDR methods

Most CDR methods face similar limitations. These include:

- Uncertainty around long-term permanence of carbon storage (especially for nature-based solutions),
- Challenges in monitoring the carbon removal,
- High costs and energy demands (particularly for engineered options),
- Trade-offs with land, water, or biodiversity (e.g. competition with food production, increased water demand, or reduced ecosystem diversity)

Also, the performance of CDR methods depends on different factors like the local biophysical conditions, governance structures, or socio-economic factors (Terlouw et al., 2021; Cobo et al., 2022). Thus, it might be hard to compare studies, as there are no generalized standards to report results.

2.1.4 Afforestation and Reforestation as a CDR

Among all CDR methods, AR is considered to be particularly attractive, as it is already reliable, cost-effective, and provides ecosystem co-benefits (Griscom et al., 2017). Unlike BECCS or DACCS, AR can be implemented using existing knowledge and infrastructure, making it an accessible option for many regions. In addition to sequestering CO_2, AR can support biodiversity, improve water regulation, enhance soil quality, and contribute to local livelihoods (IPCC, 2019).

However, AR also faces specific limitations, particularly in terms of land competition and permanence. These aspects are explored in more detail in the following sections.

2.2. Afforestation and Reforestation as a carbon removal strategy

2.2.1 Definition and scope of AR

AR is a land-based carbon dioxide removal strategy that aims to increase the terrestrial carbon sink by planting trees. Afforestation is the process of planting forests on land that has not been forested in recent history, while reforestation refers to the process of replanting trees on land that was previously forested but has since been degraded or cleared (Doelman et al., 2020). As a form of nature-based solution, AR relies on the biological process of photosynthesis to capture atmospheric CO_2 and store it in biomass and soils. AR is recognized in the IPCC's CDR classification as a mature and immediately deployable method with significant climate mitigation potential (IPCC, 2022).

Although global estimates vary, existing AR projects are currently removing between 0.77 and 1.54 $GtCO_2$ per year, with the potential to reach between 0.5 and 7 $GtCO_2$ annually by 2050, depending on location, species, and management intensity (Smith et al., 2019). However, these estimates often assume ideal conditions and do not always account for carbon losses due to land-use change, disturbances, or project implementation emissions (Lefebvre et al., 2021). Furthermore, AR takes time to deliver climate benefits, as young forests require decades to reach their maximum carbon sequestration capacity.

2.2.2 Temporal dynamics

The effectiveness of AR as a CDR method is influenced by a time factor. Unlike engineered solutions that offer near-immediate capture and storage, AR shows a delayed carbon sequestration that increases gradually over time as trees grow and ecosystems mature.

While most emissions associated with a forest project occur early in the project timeline (Gaboury et al., 2009), studies indicate that the full carbon benefits of AR may take several decades to a century to materialize (Windisch et al., 2021; Bright et al., 2012).

These time lags raise methodological challenges for climate impact assessments, especially for policies with short-term climate goals. The temporal aspect of carbon accumulation should be integrated in studies to ensure a fair assessment of AR's potential (Lefebvre et al. 2021; Terlouw et al. 2021). For this reason, some researchers argue that AR's climate benefits should be considered "effective" only when a sufficient time horizon (e.g., 80-100 years) has passed without reversal (Helin et al., 2013; Chiquier et al., 2022).

2.3 Effectiveness and permanence of AR

2.3.1 Carbon removal potential of AR

AR is widely recognized for its capacity to remove significant amounts of atmospheric CO_2 through biomass growth and soil carbon accumulation. The global carbon removal potential of AR is estimated to range from 0.5 to 7 $GtCO_2$ per year by 2050, depending on land availability, forest type, climate conditions, and management strategies (Aryapratama, 2022). Fuss et al. (2018) gets similar results, with a potential from 0.5 to 3.6 $GtCO_2$ per year by 2050.

AR's effectiveness also depends on the forest design, including species selection and planting density, or management style. Zhang et al. (2023) found that high-density plantations with strategic thinning often show greater carbon accumulation, but they also come with higher uncertainty due to biomass removals during thinning operations. Moreover, different forest types (commercial versus protection forests) show distinct sequestration dynamics. For shorter time horizons (e.g., 50 years), protection AR tends to mitigate more emissions than commercial AR; however, over a longer horizon (e.g., 100 years), managed commercial AR can store more carbon if harvested wood products are used effectively (Zhang et al., 2023).

2.3.2 Permanence and risks of reversibility

Chiquier et al. (2022) explains that there is an ongoing debate on the definition of the permanence of CO_2 sequestration. They define permanence as "the potential for CO_2 removal to be sustained for a sufficient period of time to deliver climate repair". The IPCC defines permanent carbon removal as lasting at least 100 years. AR being exposed to both natural and anthropic disturbances, the permanence of the carbon sequestration cannot be guaranteed (IPCC, 2022; Chiquier et al., 2022). These include wildfires, pests, droughts, and land-use change, all of which are expected to intensify with climate change (Kilpeläinen et al., 2022; Pan et al., 2024).

However, strategic forest management can mitigate the risk of disturbances happening. Techniques such as species diversification, reduced-impact logging, fuel management, and fire-resistant planning have been shown to increase forests' resilience and extend carbon storage duration (Zhang et al., 2023; Pan et al., 2024). Additionally, prolonging the life of wood products can delay carbon release, and improve the permanence of carbon sequestration of AR projects (Chiquier et al., 2022; Aryapratama 2022).

2.4 Environmental impacts and trade-offs of AR

2.4.1 Biogeophysical effects: cooling, albedo, and hydrology

In addition to capturing carbon, AR influence the climate system through biogeophysical effects. Forests affect surface energy fluxes by altering albedo (reflectivity), evapotranspiration rates, and surface roughness. On one hand, AR contributes to a local cooling effect, increasing evapotranspiration and precipitations. On the other hand, AR decreases the albedo in high-latitude or snow-covered regions. These effects are not to be neglected in calculations, as the albedo effect might partially offset the climate benefits of carbon sequestration, especially in the boreal zones. (Windisch et al., 2021; Kilpeläinen 2022; Bright et al., 2012)

In Europe, simulations have shown that AR can significantly alter regional precipitation patterns and temperature extremes, especially when implemented at large scale. For example, AR in northern Germany and France may result in more severe heavy precipitation events, decreasing dry days and extreme heat (Galos et al., 2013). These effects highlight the complexity of forest-climate interactions and the importance of spatially explicit planning in AR deployment.

2.4.2 Broader environmental impacts

While AR projects enhance precipitation, water retention, and provide filtering capacities, they also require substantial water resources, which might lead to a competition for land (Chiquier et al., 2022; Smith et al., 2019).

In terms of soil health, AR generally promotes soil organic carbon accumulation, reduces erosion, and improves nutrient retention over time (Smith et al., 2019). However, these benefits depend on the site's initial condition and forest management style. Intensive forestry or the use of heavy machinery can lead to soil compaction, acidification, or nutrient depletion, especially on degraded or marginal lands. AR can therefore be beneficial or detrimental depending on how it is implemented and monitored (IPCC, 2019).

Finally, while a well-designed AR project can support biodiversity restoration and improve ecosystem services, a poorly planned AR can pose serious risks to biodiversity, particularly when it involves monoculture plantations, exotic species, or afforestation of natural grasslands and peatlands (IPCC special report on climate change 2019 CHAPTER 4).

Trade-offs with food security are often overlooked, potentially leading to lower mitigation ambitions, as AR requires large amounts of land (Doelman et al.,2020). The potential of AR is limited by land availability and faces competition from other CDR methods and sectors like food and biofuels (Smith et al., 2019}).

2.5. Life Cycle Assessment (LCA) of AR projects

2.5.1 Overview

As stated by Brunori et al. (2017), a Life Cycle Assessment (LCA) is a comprehensive, objective, and internationally standardised method that quantifies energy and material flows as well as environmental and health impacts associated with products (goods or services) throughout all stages of their life cycle.It is a widely used methodology for evaluating product systems (Terlouw et al., 2021).

Compared to national greenhouse gas (GHG) inventories, which typically assess aggregated carbon flows, LCA enables more detailed accounting of upstream and downstream impacts. It also allows for the inclusion of non-carbon indicators such as biodiversity, water use, and land occupation (ISO 14040; Larrey-Lassalle et al., 2022). This makes LCA particularly suitable for analysing the complex characteristics of carbon dioxide removal (CDR) technologies such as AR (Terlouw et al., 2021).

Carbon sequestration in forestry and agro-systems has been widely studied through LCA, as noted by Brunori et al. (2017), and is exemplified by the extensive review of forestry production systems conducted by Klein et al. (2015). However, LCAs that specifically assess AR as carbon dioxide removal (CDR) strategies remain limited. Terlouw et al. (2021) reviewed the literature on LCA applied to AR and identified only four relevant studies at the time. Since their publication, only four additional studies on a similar topic have been found. As they note, research focusing on the environmental impacts of forest plantations is still scarce. Moreover, some existing studies in the AR field are only tangentially related to evaluating AR as a CDR option. For example, Chau et al. (2021) conducted an LCA on seedling growth under different shelter types, which, although relevant to the AR context, does not assess the broader environmental or climate implications of AR systems.

2.5.2 Methodological approaches in AR LCAs

The few available LCA studies on AR vary significantly in how they define their system boundaries. Most adopt a cradle-to-grave approach, covering the full life cycle from seedling production (often outside the project site) to the eventual use of harvested wood. However, there are exceptions. For instance, Gaboury et al. (2009) excluded the infrastructure production phase due to a lack of available data. Similarly, Brunori et al. (2017) limited their system boundary to on-site activities during the monitoring period and used a gate-to-gate approach.

A 100-year time horizon is commonly applied in AR LCAs. However, Aryapratama et al. (2022) chose a 200-year horizon as it seemed more appropriate for their study where long-rotation species are studied. In contrast, Brunori et al. (2017) observed their project for 34 years, offering a shorter-term perspective.

Regarding the functional unit (FU), most studies use an area-based FU, which is suitable when the goal is to quantify CO_2 uptake per hectare (Terlouw et al., 2021). For example, Lefebvre et al. (2022) and Brunori et al. (2017) use "1 reforested hectare" as their functional unit. Other studies express outcomes as CO_2 sequestered per hectare per year, as done by García-Quijano et al. (2007). In contrast, Cooper et al. (2022) use 1 tonne of CO_2 sequestered as their functional unit, which is more appropriate in their research for comparing various carbon dioxide removal (CDR) strategies. Lefebvre et al. (2022) also explored a temporal dimension by estimating the time required for one tree to capture 100 kg of CO_2.

None of the reviewed studies required allocation procedures, as AR systems typically have a single function: establishing and growing a forest (Terlouw et al., 2021), which eliminates multifunctionality concerns.

As recommended by the IPCC, the 100-year Global Warming Potential (GWP100) is the most common impact category used in these studies to capture the climate impact of the carbon flows. In addition, García-Quijano et al. (2007) also examine land use change impacts, which can be significant depending on prior land conditions.

Despite structural similarities in forest creation steps, typically including seedling production, site preparation, plantation, management, and harvesting operations, details vary greatly between studies. These variations often depend on regional context and available data. For instance, the number of seedlings planted per hectare ranges from 1'111 to 3'300, reflecting different planting densities choices. Forest management and harvesting operations are also diverse and case specific.

The modelling approaches differ across studies. García-Quijano et al. (2007) used the GORCAM model to simulate biomass growth, while Lefebvre et al. (2021) used the biomass model RothC for instance. Many authors also develop scenario-based comparisons to reflect alternative forest management strategies. Finally, Zhang et al. (2023) incorporate the substitution effect of using harvested wood to replace high-emitting materials.

The lack of standardization in LCAs for AR leads to significant variation between studies, where certain parameters, such as seedling density, management practices, or modelling choices, are detailed in some cases while not so much in others.

2.5.3 Key findings

As Terlouw et al. (2021) reported in their review, studies observed sequestrations between 0.8 and 1.0 tonnes of carbon per hectare per year. Cooper et al. (2022), in a comparative analysis of several carbon dioxide removal (CDR) methods, find that AR is the most effective in terms of climate performance, exhibiting the lowest global warming potential (GWP) among the options considered. Using a different functional unit, they estimate that AR emits 36 kg CO_2-eq per tonne of CO_2 sequestered.

In a case-specific study using biochar to improve the sequestration on site, Lefebvre et al. (2021) find that in the first year, AR resulted in a net sequestration of 0.51 tC/ha. Also, Based on a planting density of 1,111 seedlings per hectare, they estimate that it takes approximately 4.1 years for one tree to capture 100 kg of CO_2.

2.5.4 Limitation/challenges and identified gaps

LCA in the files of AR faces some limitations. One recurring issue is the lack of temporal consideration. Standard LCA models typically assume that emissions and removals are equivalent regardless of when they occur, treating carbon flows as static. This is problematic for AR, where emissions for instance from the site preparation take place immediately, while carbon sequestration happens gradually over time. To address this, dynamic LCA (DLCA) methods have been developed to include time-dependent characterization factors that better reflect the evolution of radiative forcing (Levasseur et al., 2010). These approaches are particularly relevant for AR, as highlighted by Terlouw et al. (2021), who suggest that incorporating temporal aspects could significantly affect LCA outcomes. However, such methods are still rarely used in practice, and only Aryapratama et al. (2022) applied it in the reviewed studies.

Another problem lies in the fact that some studies dont include all the activities that take place in the creation steps of the forest, such as those from infrastructure production in the case of Gaboury et al. (2009) for instance, or the seedling production and transport in the case of Brunori et al. (2017), even though they can represent a substantial share of the total footprint.

Beyond methodological gaps, there are also conceptual and practical challenges. For instance, Zhang et al. (2023) acknowledge that their study does not incorporate social or economic dimensions, a limitation that applies to the other studies reviewed as well. The overall scarcity of studies on AR constitutes a gap in itself, making it difficult to compare results across cases, especially since they are conducted in very different geographic contexts and employ varied modelling approaches. This variation further underscores the need for greater standardization in how LCA is applied to AR systems.

2.6. Comparison with other CDR methods

2.6.1 Overview of key differences

While AR is among the most established carbon dioxide removal (CDR) methods, a growing set of technological and geochemical alternatives offer different advantages and limitations. Methods such as Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), enhanced weathering, and biochar have all been proposed as ways to permanently remove CO_2 from the atmosphere (Fuss et al., 2018; IPCC, 2022).

AR stands out for its relative maturity, low cost, and multiple co-benefits including biodiversity enhancement, soil restoration, and improved local air and water quality. However, it is also land-intensive, relatively slow to deliver climate benefits, and vulnerable to reversal. In contrast, BECCS and DACCS offer more durable carbon storage through geological sequestration but require significant infrastructure, high energy input, and have high capital costs.

2.6.2 Permanence and risk of reversal

Permanence is a key differentiator among CDR strategies. AR stores carbon in biomass and soil, which is reversible due to wildfires, pests, drought, or future land-use change. (Chiquier et al., 2022). In contrast, geological storage, used in BECCS and DACCS, offers near-permanent carbon removal with very low reversal risk.

Some carbon removal methods don't store CO_2 permanently, and their effectiveness can change over time. For instance, biochar can keep carbon locked away for hundreds of years if conditions are right, but it can also break down more quickly in other environments. Similarly, enhanced weathering works slowly at first and becomes more effective over time as minerals react. So, when comparing how permanent different methods are, it's important to look at both how stable the carbon storage is and whether there are systems in place to protect it over the long term.

2.6.3 Cost, scalability, and policy readiness

CDR options also vary widely in terms of economic and operational feasibility. AR is among the least expensive methods, with costs ranging from \$5 to \$50 per tonne of CO_2, depending on the region and project design (Griscom et al., 2017). DACCS, in contrast, can exceed \$100-300 per tonne, while BECCS costs vary widely depending on the biomass supply chain and energy source used (Fuss et al., 2018; Rios et al., 2023).

In terms of scalability, technological CDR options are still in early deployment stages and require supportive infrastructure and energy systems to operate sustainably. AR, by contrast, is already being implemented at scale in many countries and is often included in Nationally Determined Contributions (NDCs) under the Paris Agreement. However, land availability and ecosystem trade-offs can constraint the expansion. Thus, most policy frameworks recognize the need for a portfolio of CDR options, rather than relying on a single method (IPCC, 2022).

2.6.4 Synergies and integration with other methods

While CDR methods are often discussed individually, combining them may increase overall effectiveness. For example, integrating AR with biochar production or using residues from forest plantations for BECCS can maximize carbon capture while generating renewable energy or soil amendments (Zhang et al., 2023; Lefebvre et al., 2021).

AR also complements engineered methods by providing ecosystem services, improving public acceptance, and supporting early-stage deployment while technological CDR continues to mature. In this sense, AR is often seen as a "no-regret" option that can be implemented immediately while contributing to both mitigation and adaptation goals, though not without careful attention to trade-offs and permanence limitations.

Chapter 3: Methodology

3.1 Introduction to methodology

This chapter presents the methodological approach used to assess the efficiency and permanence of CO_2 sequestration through AR, from a life cycle assessment (LCA) perspective. The goal is to estimate the potential amount of CO_2 that could be permanently stored by a growing forest over the defined time horizon.

The region of interest is Europe, and the objective is to present a map of AR potential across different countries. Due to time constraints, the process will be carried out in detail for one country, selected based on the potential for AR and data availability. However, the methodology can serve as a framework for application in other countries or regions.

To achieve this, different methods are used in parallel. On one hand, the emissions associated with establishing and managing a forest throughout the rotation period are calculated using the Brightway25 software. On the other hand, the amount of carbon sequestered by the forest at each age is estimated using the CO2FIX model. These two components are then combined to determine the net sequestration potential.

The methodology is organised as follows: it begins with the data collection for the different European countries, then describes the application of the CO2FIX model. Next, it explains the steps and activities modelled in Brightway25, followed by the parameters and main scenarios used. It then presents how all components are integrated within the workflow and finally outlines the analysis of results and introduces the selected country.

3.2 Regional data processing

To collect the data required for different stages of the project, several maps were created using the QGIS program. Data layers such as potential for reforestation, potential in mountain areas, and tree species distribution were prepared for this purpose. Additional regional data are also relevant, such as forest road density and meteorological data, and will be used in different parts of the life cycle assessment (LCA). This chapter details how the regional data was collected, prepared, and organized.

Part of the regional data was processed using the software QGIS. For that matter, a new project is created using the Coordinate Reference System (CRS) EPSG:3035, which is well-suited for analyses across Europe, and the pixel size is set to be 1km2. All data originating from a different CRS is first reprojected to match the project's CRS and scaling. To obtain data for each European country, a vector file containing the shapes of all countries is used, enabling spatial analysis at the national level.

3.2.1 Overview of AR potential mapping - QGIS

The first step consists in identifying areas where forest planting is possible. This is based on the work of Griscom et al. (2017), who provide a global map indicating where tree restoration could potentially take place. The map relies on ecoregional data and bioclimatic modelling to assess land suitability according to several criteria. Areas such as existing forests, regions unlikely to support forest regrowth, densely populated rural zones, agricultural lands, and other intensively used areas are excluded. Boreal regions are also removed, due to biophysical effects related to forest cover that may reduce albedo and counteract carbon sequestration. This may respond to some concerns mentioned by Windisch et al. (2021) (Section 2.4).

With the support of M. Windisch, a Boolean version of the Griscom et al. (2017) data was generated, covering the entire globe. The raster was then clipped to the extent of European countries, as the analysis is limited to Europe. The resulting map (Fig. 1) shows areas in Europe where forest restoration is considered possible (white) and areas where it is not (black). The number of pixels was then summed per country to estimate the regional potential in hectares.

***Fig. 1** Map of AR potential for Europe based on Griscom et al. (2017)*

3.2.2 Defining accessibility of the terrain

In order to define the type of forest management to be applied in each country, the accessibility of the terrain must first be assessed. Based on the Swiss National Forest Inventory (Brändli et al., 2020), three management types are identified: aerial, cable, and terrestrial (see Section

3.4.3). For each country, two or three of these management styles are applied, with their respective shares depending on terrain accessibility.

It is assumed that mountainous areas require more aerial management, while regions with limited forest road access require more cable management. Therefore, the share of each management type is defined based on terrain accessibility.

Mountainous areas

In this analysis, mountainous terrain is defined as areas located above 600 meters in elevation. This threshold was selected to align with the elevation categories used in Swiss forest data by Brändli et al. (2020).

To estimate mountainous forest potential, a European elevation map from Open Maps For Europe and EuroGeographics[5]. was used to create a mask with all areas above 600 m. This mask was applied to the AR potential map, producing a new layer showing only areas suitable for AR within mountainous terrain (Fig. 2).

The number of hectares located in mountainous regions was then calculated for each country. To estimate the share of aerial management, data from Switzerland was used as a reference: 83.1% of forests lie above 600 m, and 21% of forest management in all forest is done with aerial transport. A linear relationship was assumed between the share of potential AR land above 600 m and the expected share of aerial management, and this was applied to other countries accordingly.

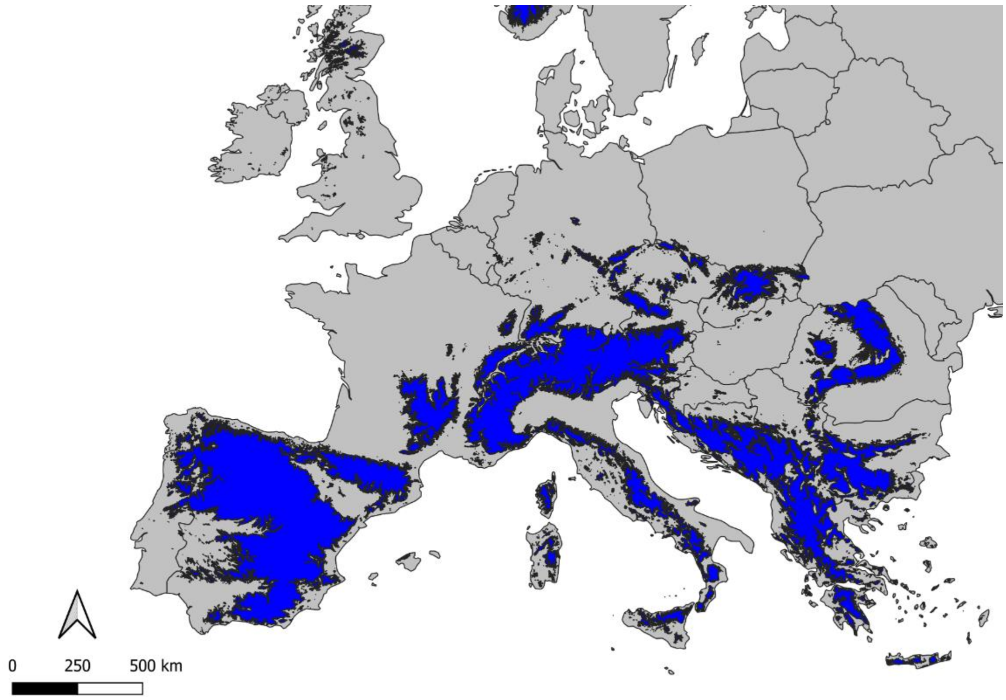

Fig. 2 *Map of areas located above the 600 m elevation threshold (blue) for Europe*

[5] © EuroGeographics 2025

Road density

Similarly, the type of forest management is further assessed, this time using forest road density. While mountainous terrain was previously used to estimate the need for aerial management, cable management is also typically required in areas with limited accessibility. In this case, forest road density is used as an indicator: the assumption is made that the higher the road density, the easier it is to access forest sites, and the lower the expected need for cable yarders.

Road density data for most European countries are available in Pucher et al. (2023), who provide average values for five European regions[6]: North, Central West, Central East, South West, and South East. The corresponding forest road densities for these regions are 9, 30.2, 17.7, 19.5, and 11 meters per hectare, respectively. Some countries are not explicitly represented in this regional breakdown, and thus all countries that were not excluded were assigned to the region that best fit their geographic and infrastructural characteristics[7]. These average values can be used as default estimates but may also be replaced by actual country-level data when available.

Knowing the road density for each country, as well as the value for Switzerland (25.7 m/ha), the share of cable management was extrapolated using a linear relationship, based on the 24% of cable management observed in Switzerland (Brändli et al. 2020).

Finally, the share of terrestrial management was calculated as the remaining percentage after determining both aerial and cable shares.

3.2.3 Tree species distribution and dominance - QGIS

Using data from Brus et al. (2011), the three most widespread tree species were identified for each country. The dataset is provided in the form of maps indicating regions where different species are likely to grow. By overlaying these maps with the map of potential forest areas, it was possible to determine the most represented species within the afforestation potential zones for each country. This was done by performing a zonal histogram analysis.

The three most dominant species in potential AR areas were then used to determine their respective shares, which serve as a basis for estimating biomass dynamics. The biomass accumulation for each country is modelled using these three species, constructed within the CO2FIX model (see Section 3.3).

[6] **North Europe**: Denmark, Estonia, Finland, Latvia, Lithuania, Norway, Sweden
Central-West Europe: Austria, Belgium, France, Germany, Ireland, Liechtenstein, Luxembourg, The Netherlands, Switzerland, United Kingdom
Central-East Europe: Czech Republic, Hungary, Poland, Romania, Slovakia
South-West Europe: Italy, Portugal, Spain
South-East Europe: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Montenegro, North Macedonia, Serbia, Slovenia

[7] **North Europe**: Denmark, Iceland
Central-East Europe: Belarus, Ukraine

3.2.4 Meteorological data

In order to construct accurate biomass accumulation models using the CO2FIX model (see Section 3.3), meteorological data on temperature and precipitation are required. The most complete and extensive dataset available for most European countries was found in the Global Climate Data provided by the Deutscher Wetterdienst (2024).

The dataset used consists of multiple stations per country, providing monthly mean temperatures, deviations from the 1991-2020 average, and monthly precipitation means for the year 2024, as no more representative average was available. The data were processed to calculate the monthly mean temperature for each country by averaging the values from all stations within that country.

This dataset covers most European countries but can be replaced by more accurate or localized data if needed/available for a country-specific analysis. For countries where punctual station data were missing, values from the previous year were used as substitutes.

3.2.5 Exclusions

For practical reasons, certain countries were excluded from the study.

Russia was not included, as it does not perform well under the chosen Coordinate Reference System (EPSG:3035), which may lead to distortions and inaccuracies in spatial analysis.

Additionally, countries such as the Vatican, Monaco, Andorra, and San Marino were excluded due to their very small size and limited data availability.

Finally, Albania, Kosovo, Liechtenstein, and North Macedonia were excluded from the analysis because of insufficient meteorological data.

3.3 Biomass modelling approach - CO2FIX

To accurately represent the CO_2 sequestered by the growing forest, the CO2FIX model was selected. This chapter briefly explains how the model works and how it is applied in this study.

3.3.1 Overview of CO2FIX V3.1 model

CO2FIX is a stand-level simulator that operates with one-year time steps to quantify carbon stocks and fluxes in forest biomass, soil organic matter, and wood product chains. The model can also include financial aspects and account for carbon credits. With relatively limited input data, it generates graphs and tables that help estimate the evolution of carbon across different pools. It is applicable to a variety of land use situations, including afforestation, agroforestry systems, and selective logging systems.

All information regarding the use of this model is based on the report *CO2FIX V 3.1 - A modelling framework for quantifying carbon sequestration in forest ecosystems* (Schelhass et al., 2004). Further details can be found in that document.

This model was selected to simulate tree growth because it requires relatively few input data while accounting for multiple parameters that would be too complex to reproduce using simple equations. It is also user-friendly, and the results it produces are straightforward to interpret and use.

3.3.2 Model settings

The interface provides access to several modules for project configuration. The modules and the corresponding settings applied in this study are presented below, following the sequence in which they appear in the programme. The settings presented here are the ones applied for any regions, the regional settings are detailed in the case study in the Section 3.9.

General Parameters

The first step is to define the general parameters used in the model. The CO2FIX model operates on a cohort-based approach. However, in this study, only single tree species are considered, in order to limit complexity. As a result, each scenario models the growth of one specific tree species over its lifecycle, including harvesting at the end of the designated rotation period. Each cohort is defined as either a broadleaved or coniferous species, depending on the characteristics of the tree being modelled.

Tree growth is simulated as a function of age over a 450-year period, following the approach used for the two example species provided with the model.

Biomass Module

With the general structure defined, the biomass parameters are now set to simulate tree growth. For each species, specific parameters must be adjusted. The core element of the biomass module is stem growth, for which current annual increment (CAI) values must be provided in units of [m^3/ha/year]. These values are species-specific and can be sourced from the EFISCEN Inventory Database (Schelhaas et al., 2006), or from individual studies found in the literature.

The carbon content is set at 0.5 MgC/MgDM for all species, in line with commonly accepted values in the literature (Schelhaas et al., 2006). The initial carbon stock is set to zero, representing a newly planted forest.

Growth of foliage, branches, and roots is modelled in relation to stem growth. As reliable data for these components is difficult to find for all species, the choice was made to represent only coniferous and broadleaved species. For coniferous species, the growth data was taken directly from the example of Norway spruce. As no example for broadleaved species was available, the growth of foliage, branches, and roots is modelled using data from Sheshnitssan et al. (2024).

To keep the model as simple and time-efficient as possible, mortality and competition are generally not included.

Thinning and harvesting parameters such as the timing of thinning operations and the amount of biomass removed are specified using a management table. At the end of the rotation period, a final felling is performed, during which all biomass is harvested and the stand is replanted. The thinning schedule applied in this study (management regime) is presented in Section 3.5.2.

Unless otherwise specified, the managed biomass is automatically allocated to the soil carbon stock. However, in this study, the harvested wood is assumed to be used for energy production (see Section 3.4.3). A share of biomass remains in the forest and the rest is extracted for energy production in this study.

Soil Module

To calculate soil carbon dynamics, the model requires input values for degree days above zero and potential evapotranspiration during the growing season. These are determined using the model's built-in calculator, which relies on the monthly mean temperature and precipitation of the selected area. The temperature and precipitation data used for this calculation are presented in Section 3.9. In addition, the growing season must be specified for each tree species.

Other parameters related to soil activity can also be defined manually. However, in this case, the default settings from the integrated Yasso model are used.

Product and Bioenergy Module

The CO2FIX model includes a module for simulating scenarios where harvested biomass is converted into products or used for energy, allowing for the estimation of carbon storage and substitution effects. However, apart from getting slashwood out of the forest via the 'product' section, all other aspects of this module are not included in the study.

Since the internal calculations of the CO2FIX module are not fully transparent, and all emissions related to woodchip processing, transport, and combustion are already accounted for in the life cycle assessment conducted in Brightway25, this component was excluded to avoid the risk of double counting or omission. Despite this, the module may offer potential for further research focused specifically on carbon substitution or product life cycles.

3.4 Life cycle modelling approach - Brightway25

3.4.1 Overview

System boundaries

A cradle-to-grave approach is applied, meaning that all activities are considered from the moment seedlings are produced in the nursery until the wood is used after harvesting. In this study, it is assumed that all wood removed from the forest, whether it is during forest management operations or at the end of the rotation period, is transformed into wood chips for energy production. This assumption is made to avoid introducing too many different scenarios and to maintain consistency across the analysis.

Time Horizon

To remain consistent with similar studies, a time horizon of 100 years is selected. As part of the sensitivity analysis, the time horizon of 50 and 200 years will also be tested. All calculations assume a starting date of January 1st, 2024, and all durations are expressed relative to this reference point.

Functional Unit

The functional unit used is one hectare of reforested land, from growing seedlings to energy production, over a 100-year period. As all processes are modelled for one hectare, the results can easily be scaled to represent the potential of larger areas.

Impact Categories

In line with IPCC guidelines and recommendations from the literature (Aryapratama et al., 2022; Brunori et al., 2017; Lefebvre, 2021; Levasseur et al., 2010), the impact category selected for this study is the Global Warming Potential over a 100-year time horizon (GWP100). The specific method used is the IPCC 2021 (including biogenic CO_2), as implemented in the ecoinvent 3.11 database, under the category "climate change: total (including biogenic CO_2)". This method accounts for all sources of greenhouse gases, including those of biogenic origin, and expresses their impact in terms of kg CO_2-equivalent over 100 years.

3.4.2 LCA software and interface

The software used for emission calculations in this project is Brightway25, the latest version of Brightway2. It is an open-source tool designed for conducting life cycle assessment (LCA) and impact assessment using the Python programming language.

Initially, the Activity Browser interface was used to model the activities in a user-friendly environment. Later, the analysis was continued in Jupyter Notebook to take advantage of additional features offered by the software, particularly the dynamic dimension, which is relevant for modelling forestry systems over time.

All background data were sourced from Ecoinvent 3.11 with the cut-off system model. The scaling of activities was based on values found in the literature.

3.4.3 Forestry activities modelling

The objective is to model the full lifecycle of a forest system from cradle to grave as accurately as possible. The model is designed to be adaptable to different regions, with adjustable parameters that reflect regional variations. In the scaling hereafter, the formulas are described with the parameters per default, but can then be changed to better reflect the situation of a specific project or country.

The choice of the region for an activity was made as much as possible to represent Europe (RER next to their name), but when not possible, data from Switzerland (CH), or the rest of the world (RoW/GLO) was used. We assume that they still represent the emissions of a forest project in Europe.

When modelling the use of a machine that requires fuel, all fuel-related emissions are accounted for directly in the activities.

The process begins by creating the necessary databases, which contain all custom-built activities used in the model. A graph of how the activities are linked is provided in Appendix A, in which the numbers correspond to the number of the activities hereafter. More detailed explanations of how each foreground activity is constructed are provided in the following section:

1. **"1 ha of forest"**: It is the functional unit and includes all activities required to establish 1 hectare of forest. At the end of the calculation, the total emissions associated with the planting of 1 hectare of forest, based on the parameters used to represent a given situation, are obtained. This result can then be scaled up to represent larger areas.

   This activity is linked to activities 2, 3, and 4. Activities 2 and 3 are scaled per hectare and are therefore linked directly, without additional calculations. Activity 4, on the other hand, is scaled in tons and is multiplied by the amount of wood managed or harvested during the timeline creation process.

2. **"preparing site prior to planting"**: The first activity taking place on the future forest site is site preparation. It begins with a one-hectare plot of land covered with existing vegetation and ends with the same area cleared and ready for planting, including the construction of an access road. This step involves two main operations: the removal of existing vegetation using a mulcher, and the construction of a gravel road. It is assumed that the future forest site is covered with mild vegetation that can be easily removed using a mulcher. The terrain is not considered particularly difficult and does not require any additional preparation beyond standard site-clearing activities to make it suitable for tree planting. The dimensions of the road are regionally defined, and the total length depends on the region of Europe, as explained in Section 3.2.2.

   Four Ecoinvent processes are involved in this activity. The first is "mulching - CH", which is already scaled for one hectare and therefore requires no adjustment. The second is "market for gravel, crushed - CH", defined per kilogram of gravel and rescaled according to road dimensions and gravel density, using the following formula[8]:

$$gravel\ [kg/ha]\ =\ road\ density\ [m/ha]\ *\ size\ of\ the\ road\ [m2]\ *\ 1500\ [kg/m3]$$

The gravel is transported to the site using the process “market for transport, freight, lorry, unspecified - RER”, scaled based on the amount of gravel and the distance between the production site and the forest. The gravel market already includes 20 km of transport; any additional distance is handled by a parameter, which is set to zero by default:

$$transport\ [ton * km]\ = gravel[t]\ *\ km\ gravel[km]$$

Before laying the gravel, the roadbed is excavated using an excavator “market for excavation, skid-steer loader - GLO”, based on the road’s volume:

$$excavation\ [m3]\ = road\ volume\ [m3]$$

It is assumed that building the road does not require any additional steps.

3. **“planting forest - seedling and plantation”:** This activity models the process of planting seedlings. It begins with seedling production in a nursery and ends with a one-hectare field planted with young trees. The process includes the construction of a greenhouse, fertilization, packaging and transport of the seedlings, as well as the disposal of packaging materials.

   Three Ecoinvent processes are used in this activity. The first is "market for seedling, for planting - RER", which represents the emissions associated with producing one seedling in Europe. This activity is multiplied by the number of seedlings required per species. The second is "market for planting - GLO", which is already scaled for one hectare and represents the operation of a planting crew using agricultural machinery. This process does not include the seedlings themselves, which is why it is combined with the seedling market activity..

   Finally, the seedlings also need to be transported from the nursery to the forest site (“market for transport, freight, lorry, unspecified - RER”). The transport is scaled based on the distance separating both sites, as well as the weight of the seedlings. It is decided that all seedlings from different species have the same weight, as a difference of a few grams is assumed to not impact the results.

$$transport\ [ton * km]\ = weight\ seedling[t/unit]\ *\ nb\ seedling[unit]\ *\ km\ seedling[km]$$

4. **“forest management and energy”:** This activity models both the forest management/harvesting operations and the energy substitution resulting from the use of harvested wood. Management refers to thinning part of the biomass as a maintenance operation, while harvesting refers to the complete removal of forest

[8] Gravel density: 1500 kg/m3, from https://gravier.geomaterio.fr/articles/informations-pratiques/masse-volumique-gravier

biomass. The activity starts with a growing forest and ends at the power plant, where the wood, converted into woodchips, is used to produce energy.

The model accounts for emissions associated with the production of 1 ton of wood (whether managed or harvested) and includes the transport of woodchips from the forest site to the power plant. Transport is represented by the process "market for transport, freight, lorry, unspecified - RER", and is scaled according to the following formula:

$$transport\ [ton * km] = 1[t] * km\ chips[km]$$

Two foreground activities are involved: 'managing forest' and 'energy substitution', further detailed as activities 5 and 9.

The activity 'energy substitution' is already defined per ton of wood, but applying it directly with a factor of 1 would imply that the entire energy mix is fossil-based, which is not a realistic assumption. To reflect actual conditions, this activity is scaled by the percentage of the primary energy mix derived from fossil fuels. The activity *'managing forest'* is based on the processing of 1 m³ of wood. To ensure consistency and correct scaling for 1 ton of wood, we apply the following conversion:

$$amount\ 'managing\ forest'\ [t] = managing\ forest\ [m3] * wood\ density\ [t/m3]$$

5. **"managing forest":** This activity represents the management or harvesting of 1 m³ of wood from the forest. It begins with a growing forest and ends with woodchips ready for transport to a power plant.

   To model wood extraction, three management styles were included: aerial, cable, and terrestrial, based on data from Brändli et al. (2020), which provides good insights into forestry practices and machinery commonly used under different terrain conditions in Switzerland. These three styles reflect varying levels of terrain accessibility. It is assumed that a similar distribution of practices applies across Europe. For each country, the proportional use of each management type was estimated based on terrain difficulty (see Section 3.2). For instance, mountainous countries are expected to rely more heavily on aerial methods due to limited road access. The three management styles are defined hereafter as activities 6 to 8.

   In addition, this activity includes the use of a mobile wood chipper "wood chipping, mobile chipper, at forest road - RER", which processes the managed or harvested wood into woodchips suitable for transport. It is assumed that the wood is brought to the forest road during the management phase. The chipping process is scaled according to the volume of harvested wood (here, 1 m³) and the productivity values reported by Yoshida et al. (2016), who estimate a processing capacity of 68.2 m³ per hour for a comparable mobile chipper.

$$use\ of\ wood\ chipper[hours] = 1\ [m3]\ /\ 68.2\ [m3/h]$$

6. **"managing forest - aerial":** This activity models forest management using a helicopter to transport the harvested wood from the cutting site to a road or designated

location. This technique is typically used in mountainous regions where road access is limited or difficult. The activity begins with a growing forest, includes tree cutting with a chainsaw and preparation for transport using a harvester, and ends with the wood delivered by helicopter to a specific location, where it will later be processed into wood chips.

Three Ecoinvent activities are called and must be rescaled to represent the processing of 1 m3 of wood.

The first one, "market for transport, helicopter, kerosene - GLO", is scaled according to the productivity estimate provided by Manzone et al. (2011), which states that a helicopter requires 2.5 minutes to move 1 m³ of wood.

$$use\ of\ helicopter\ [hours]\ = 1[m3]\ *\ 2.5/60\ [hours/m3]$$

The activity "power sawing, without catalytic converter - RER" is scaled based on Kent et al. (2011), who report a time requirement of 11.53 minutes to process 1 m³ of wood:

$$use\ of\ chainsaw\ [hours]\ =\ 1\ [m3]\ * 11.53/60\ [hours/m3]$$

The activity "harvesting, forestry harvester - RER" is scaled based on the productivity value from Lazdiņš et al. (2016), which indicates that 5.312 m³ of wood can be harvested per hour:

$$use\ of\ harvester\ [hours]\ =\ 1[m3]\ * 1/5.312\ [hours/m3]$$

7. **"managing forest - cable":** This activity represents the emissions associated with cutting trees on-site using a chainsaw, followed by the transport of the harvested wood using a cable yarding system. This method is applied in areas of the forest that are difficult to access. The activity starts with a growing forest, includes tree felling with a chainsaw, and the use of a cable yarder to transport the wood to the roadside. It ends with the wood being processed by the processor attached to the yarder.

   Two Ecoinvent activities are used. The first is the power saw process described in the 6th activity. The second is "yarding and processing, mobile cable yarder on truck - RER", which is scaled according to Gümüş et al. (2023), who report that the system can process 0.95 m³ of wood per hour:

$$use\ of\ cable\ yarder\ [hours]\ = 1\ [m3]\ /\ 0.95\ [m3/h]$$

8. **"managing forest - terrestrial":** This activity starts with a growing forest, involves the use of a chainsaw on-site and a skidder to transport and process the wood, and ends with the wood ready to be chipped.

   It includes two Ecoinvent activities. The first is the power saw process described in the 6th activity. The second is "skidding, skidder - RER", which is scaled based on data from Mousavi (2012). According to this source, a skidder operates in 16-minute cycles and can transport 2.5 m³ of wood per cycle. The scaling is applied accordingly:

$$use\ of\ skidder\ [hours]\ =\ 1\ [m3]\ * 16/60\ [h/cycle]\ * 1/2.5\ [m3/cycle]$$

9. **“energy substitution”:**This activity models the substitution of conventional energy sources by energy generated from the woodchips produced during forest management and harvesting operations. The energy production is divided into two parts, heat and electricity, based on the regional energy consumption mix.

   To represent this, the Ecoinvent process “heat and power co-generation, wood chips, 2000 kW, state-of-the-art 2014 - CH” is used twice: once for the heat output (in MJ) and once for the electricity output (in kWh). However, since this activity already includes the emissions associated with woodchip production, which are accounted for separately in our model, the original dataset is slightly modified to exclude those inputs.

   According to the default scaling in the dataset, producing 1 MJ of heat requires 0.0486 kg of dry wood, and 1 kWh of electricity requires 1.03 kg of dry wood. As our model operates using an input quantity of wood, both activities are rescaled accordingly:

$$heat\ [MJ]\ =\ share\ heat\ *1000\ [kg]\ \ /\ 0.0486\ [kg/MJ]$$

$$electricity\ [kWh]\ =\ (1-share\ heat)\ *1000\ [kg]\ \ /\ 1.03\ [kg/kWh]$$

   The second part of the activity accounts for the substitution effect: the energy produced from woodchips is assumed to replace energy that would otherwise have been generated using the regional electricity and heat mixes. To model this, we calculate the amount of avoided emissions by subtracting the equivalent energy from regional sources, using the same amount of heat and electricity that was generated from woodchips.

   The avoided amounts are calculated as follows:

$$avoide\ heat\ [MJ]\ =\ -1\ *share\ heat\ *1000\ [kg]\ \ /\ 0.0486\ [kg/MJ]$$

$$avoided\ electricity\ [kWh]\ =-1\ *\ (1-share\ heat)\ *1000\ [kg]\ \ /\ 1.03\ [kg/kWh]$$

   In this way, we account for both the emissions from producing energy using woodchips and the avoided emissions from displacing fossil-based energy production.

3.4.4 Time dimension

After creating and linking the activities in Activity Browser, the database is loaded into a Jupyter Notebook to continue the workflow and perform the life cycle assessment.

At this stage, the time dimension is added to activities that occur at specific moments or are repeated throughout the system’s lifespan. Forest management operations take place periodically over time, as well as the energy substitution. And the planting of the seedlings happens after each rotation period.

To model this in python, two vectors are defined for each time-dependent activity: one specifies the years in which the activity takes place, and the other defines the amount of activity occurring in each of those years. The vectors are defined per species and per scenario in the parameters (SEE PARAMTER TABLE). This allows the database to be dynamic and builds a timeline of emissions over the entire time horizon.

3.5 Parameters and scenarios

The following sections describe the parameters that can be adjusted to reflect a specific region, tree species, or scenario, and present the three main forest management scenarios considered in this study.

3.5.1 Regional and general parameters

Table 1 presents the parameters used to adapt the framework to a specific region. These include both regional characteristics and general values that remain constant across all main scenarios (see Section 3.5.1). Based on literature and other data sources described in Section 3.2, these parameters are tailored to the selected region and remain fixed throughout the evaluation of forest potential.

Table 1 *Regional and general parameters*

Parameter	**Unit**	**Description**	**Sources**
3 Main tree species	-	Main tree species present in areas available for AR. Identified based on data from Brus et al. (2011).	See section 3.2
meteorological data	-	Mean temperatures (1991-2020) and precipitation for the year 2024 in European countries. Based on data from the Deutscher Wetterdienst (2024).	See section 3.2
share of species	% [vector]	The shares of the three main species are adjusted so that, together, they account for 100% of the trees included in the scenario.	See section 3.2
aerial management	%	Share of aerial management, assumed based on the proportion of mountainous terrain in a region.	See section 3.2
cable management	%	Share of cable management, assumed based on the forest road density of a region.	See section 3.2
terrestrial management	%	Remaining share of management assumed to be terrestrial, calculated after allocating aerial and cable management.	See section 3.2

forest road density	m/ha	Used to estimate the required amount of gravel for road construction and to assess terrain accessibility.	See section 3.2, or regional literature
forest road dimension	m2	Road profile area used with road density to calculate total gravel volume needed for construction.	Regional literature
transport distance of seedlings	km	Distance from the nursery to the forest site.	Regional literature
transport distance of gravel	km	Distance from the quarry to the forest site for road construction.	Regional literature
transport distance of woodchips	km	Distance from the forest to the power plant where woodchips are used for energy production.	Regional literature
share of heat in the energy mix	%	Share of heat in energy demand used to allocate impacts in co-generation (heat and electricity).	Regional literature
share of fossil in the energy mix	%	Share of fossil fuels in the energy mix, used to determine the substitution potential when woodchips replaces fossil-based sources.	Regional literature
seedling weight	ton	Default value: 0.0005 ton (5 g). Based on Devetaković et al. (2019) for oak; assumed the same for all species due to negligible variation at the project scale.	Devetaković et al. (2019)
potential for AR	ha	Total area allocated potentially for AR in the project (or country).	See section 3.2
time horizon	years	Duration of the project or assessment. Default value: 100 years	-

3.5.2 Tree species specifics parameters

Table 2 presents the parameters specific to each tree species, which are later detailed in the case study.

Table 2 *Tree species specific parameters*

Parameter	**Unit**	**Description**	**Source**
number of seedlings per hectare	unit	Number of seedlings to plant per hectare for a given species.	Regional literature
thinning and harvest years	years [vector]	Years when thinning operations (or final felling) are scheduled, based on the management regime of the	See section 3.5.3

		scenario.	
share of biomass removed	% [vector]	Proportion of standing biomass removed during thinning operations.	See section 3.5.3
extracted biomass	ton/ha [vector]	Amount of biomass (in tons per hectare) removed from the forest during thinning or final felling. Values are calculated within the CO2FIX model.	Calculated in CO2FIX
rotation period	years	Length of the full rotation cycle before final felling and replanting.	(Regional) literature
wood density	t/m3	Average wood density for the species.	(Regional) literature

3.5.3 Main Scenarios

The base scenario (business as usual) represents the state of the land without AR implementation. In this scenario, no additional CO_2 sequestration from afforestation or reforestation occurs, and the land continues under its current use or natural state. All AR scenarios are evaluated against this baseline to quantify the additional carbon sequestration achieved.

To assess the sequestration potential of AR, three scenarios are defined, each representing a different forest management strategy. These scenarios vary solely in management style, while all other parameters remain constant. The configurations are inspired by Juodvalkis et al. (2005) and are described below. The input data used in the CO2FIX and Brightway25 models is summarized in Table 3.

Scenario 1 - no management

In this scenario, the emissions of the site preparation and planting the forest occur during the year 0, and then left unmanaged. No harvesting takes place either. The mortality rate of trees is set to 1%, but all dead trees remain in the forest.

Scenario 2 - medium management

This scenario represents what will be used as the standard treatment. The emissions of the site preparation and planting the forest occur during the year 0. Then the forest is managed in a moderate way : the first thinning operations occur at year 10, then every 10 years during the first 30 years of the forest, then every 12 years during the next 30 years, and finally every 15 years until the end of the rotation period.

Each thinning operation removes 25% of the current biomass, and at the end of the rotation period, the 100% of the biomass is harvested. From what is thinned/harvested, 15% remains in the forest, and the remaining 85% are turned into woodchips for energy production.

The year after the final harvesting, the forest is replanted and everything is repeated for as long as the time horizon permits it.

Scenario 3 - heavy management

The last scenario represents a heavy management. The emissions of the site preparation and planting the forest occur during the year 0. The first thinning operations occur at year 10, then every 5 years until the end of the rotation period.

Each thinning operation removes 40% of the current biomass, and at the end of the rotation period, the 100% of the biomass is harvested. From what is thinned/harvested, 5% remains in the forest, and the remaining 95% are turned into woodchips for energy production.

The year after the final harvesting, the forest is replanted and everything is repeated for as long as the time horizon permits it.

Table 3 *Configuration of the main scenarios*

	No management (scenario 1)	**Moderate management (scenario 2)**	**Heavy management (scenario 3)**
Management years	[]	[10,20,30,42,54,66,81,96,111,126]	[10, 15, 20, 25, …]
Percentage of biomass thinned	[]	[0.25]	[0.40]
Percentage of wood left in the forest	[]	0.15	0.05

For all scenarios, the management years are adjusted accordingly to match each species' rotation period.

3.6 Workflow Integration

At this point, everything needs to be brought together to create the scenario for our forest. The objective is to assess the potential of AR in Europe, but with a focus on each country or region separately. The idea is to provide a flexible framework that can be applied to any region, calibrated with specific parameters and variables. The general structure of the system is illustrated in Figure 3, where one can see that two systems work side by side (Brightway25 and CO2FIX), and that they are connected together through the wood harvesting.

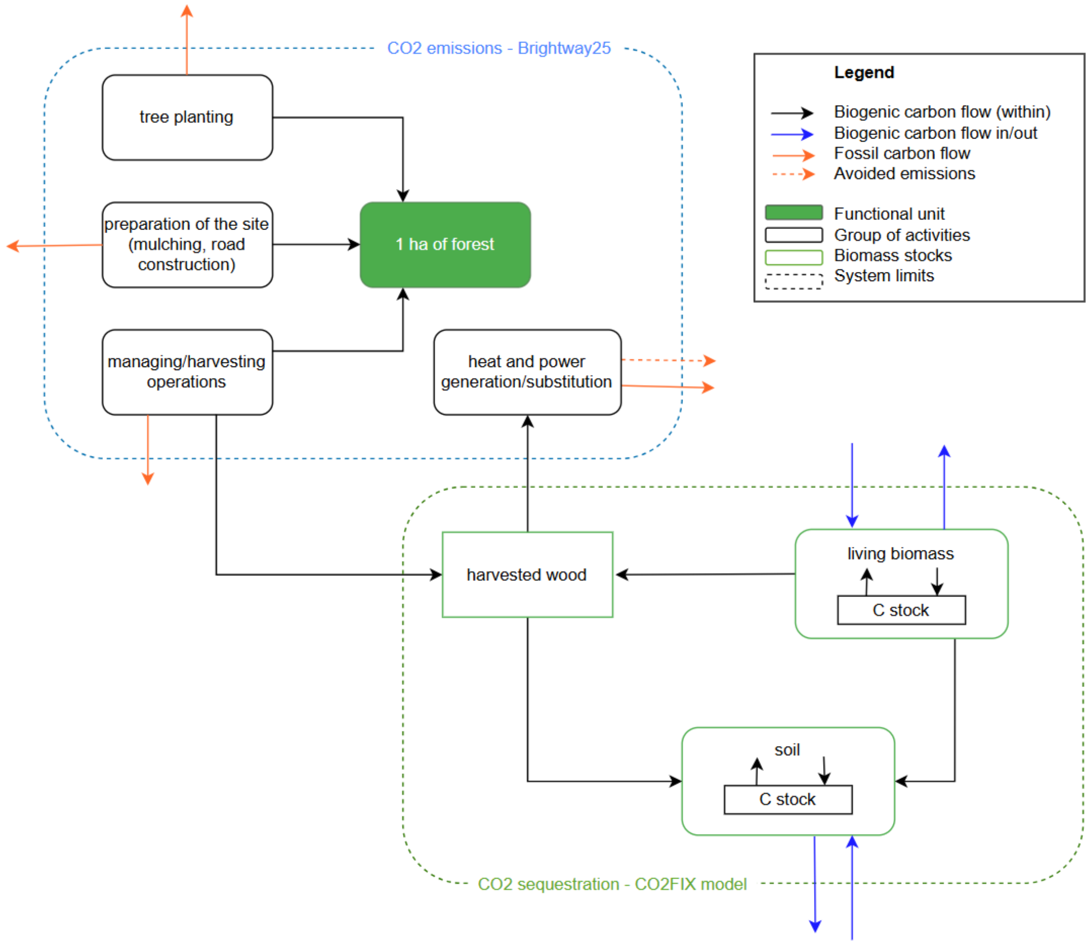

Fig. 3 *System boundaries and carbon flows for the study, combining the LCA model (Brightway25) and the CO2FIX model. The functional unit is 1 ha of forest.*

The process begins with the choice of a region. In this context, data for most European countries has already been computed (see Section 3.2), so in theory, any country can be represented. For this study, the focus will be on the country with the highest potential for AR, based on the explanations provided earlier. This case will be presented in Section 3.9.

Once the country is selected, the parameters presented in Section 3.5 need to be adjusted accordingly.

Everything is integrated and executed in Python. A dedicated notebook is used to load all necessary databases and files: the Ecoinvent 3.11 database and the foreground process database for the LCA, the country- and species-specific parameters, and the total sequestration and wood harvested data for each tree species in the scenario.

The scenario assembly and execution follow these steps:

1. **Parameter setup:** The parameters are set according to the selected country and tree species.

2. **CO2FIX modelling:** Each tree species is modelled individually in CO2FIX to generate the sequestration and wood harvested data.

3. **Data loading in Python:** The CO2FIX results, along with the Ecoinvent 3.11 and foreground activities, are loaded, and all parameters are applied.

4. **Dynamic LCA:** For each tree species, the LCA timeline is created, with site preparation at year 0, planting operations at year 0 and after each rotation period, and management operations during the designated years for the amounts defined in the parameters. This produces three sets of yearly emissions.

5. **Net sequestration calculation:** The yearly emissions obtained at the former step are combined with the CO2FIX sequestration data to calculate the yearly net sequestration. All data are converted in order to get the results in tons of CO_2-eq.

6. **Regional sequestration:** The regional net sequestration is then calculated by proportionally combining the results for the three species based on their respective shares.

This framework can be applied to multiple scenarios to assess net sequestration over a chosen time horizon and can also be adapted to a specific region or individual forest project.

3.7 Assumptions and limitations

This chapter presents the main assumptions and limitations of the study. Assumptions are the conditions defined for the modelling, while limitations are factors that can reduce the accuracy or applicability of the results. Sometimes a point can be both an assumption and a limitation, for example when a simplification is necessary for the model but also reduces how much the results can be applied elsewhere.

A detailed list of the assumptions/limitations is provided in Appendix B. In summary, the assumptions cover four main areas:

- Regional assumptions, including climate input data and terrain definitions.
- LCA-related parameters, including time horizons, transport distances, road construction materials, and energy production shares.
- CO2FIX model parameters, such as species-specific growth rates, wood densities, biomass allocation, mortality rates, and the exclusion of natural disturbances.
- Other general considerations, such as the exclusion of socioeconomic constraints or ecosystem co-benefits.

These assumptions define the boundaries and input conditions of the study and, in some cases, also represent limitations that may influence the results.

3.8 Sensitivity analysis

The sensitivity analysis is based on the second scenario, designated as the standard scenario. Several parameters (Table 4) are varied by +20% and -20% to assess their influence on the results. The parameters were selected based on their relevance and possibility to be adjusted within the model. They include road density, road size, share of heat in energy production, distance from quarry to forest, distance from nursery to forest, and distance from forest to power plant.

Additional tests include multiplying the seedling weight by 100 to explore its effect, and replacing the original mixed-share management approach with a single management style (aerial, cable, or terrestrial) to evaluate their individual impacts. The scenario is also rerun with alternative time horizons of 50 years and 200 years, in addition to the standard 100-year horizon, to assess the effect of time horizon length on net balance emissions outcomes.

The analysis focuses on three metrics: (1) total project emissions from the LCA, (2) biomass sequestration, and (3) net sequestration, defined as biomass sequestration minus total emissions. These metrics are assessed in both absolute terms and as annual averages over the time horizon, and are also expressed relative to the standard scenario (scenario 2).

Table 4 *Overview of all scenarios used in the sensitivity analysis variations*

name of the scenario	**description**
scenario 1	no management of the forest after planting
scenario 2	moderate management of the forest after planting - standard scenario
scenario 3	heavy management of the forest after planting
road d plus	+20% of road density
road d minus	-20% of road density
road s plus	+20% of the road dimensions
road s minus	-20% of the road dimensions
seed plus	+20% in the seeds amount
seed minus	-20% in the seeds amount
weight seedling	weight multiply by 100 (500g)
heat plus	+20% of the share of heat
heat minus	-20% of the share of heat
kmgravel plus	+20% distance career-forest
kmgravel minus	-20% distance career-forest

kmseed plus	+20% distance nursery-forest
kmseed minus	-20% distance nursery-forest
kmchip plus	+20% distance forest-power plant
kmchip minus	-20% distance forest-power plant
50 years	time horizon decreased to 50 years
200 years	time horizon increased to 20M0 years
manag aerial	only aerial management of the forest
manag cable	only cable management of the forest
manag terrestrial	only terrestrial management of the forest

3.9 The case of Ireland

Ireland has set ambitious climate goals, committing by law to reduce greenhouse gas (GHG) emissions by at least 7% per year over the next decade and to reach climate neutrality by 2050 (Taoisigh, 2025). Achieving net zero means balancing or exceeding GHG emissions with removals.

In 2024, Ireland's total GHG emissions (excluding those from land use, land-use change, and forestry) amounted to 54 Mt CO_2-eq, a 2 % decrease compared to 2023 (EPA, 2025).

Forestry expansion is recognised as one of the strategies to support Ireland's net zero target. Farrelly and Gallagher (2015) note that the government aims to increase productive forest area to 18 % of the national territory by 2046, requiring the planting of approximately 490 000 ha of new forest.

3.9.1 Regional data for Ireland

Potential for AR

After computing the map of AR potential across Europe, Ireland appears to have the highest relative potential. As shown in white in Figure 4, it totals 5'231'700 hectares (5.2 millions ha) of eligible land (see Section 3.2), which corresponds to 76% of the country's total surface area.

Fig. 4 *Map of AR potential for Europe based on Griscom et al. (2017)*

Terrain accessibility

Very few mountainous areas are present in Ireland (elevations above 600 m), as shown in blue in Figure 5, and according to Dolan et al. (2024), the forest road density is 23.21 m/ha, indicating sufficient terrain accessibility. As a result, most of the biomass transport can be carried out and processed by terrestrial management.

Fig. 5 *Map of areas located above the 600 m elevation threshold (blue) for Europe*

Meteorological data

Meteorological data from the Deutscher Wetterdienst (2024) (see Section 3.2) provide mean monthly temperatures for the period 1991–2020, as well as precipitation values for 2024 (Fig. 6). No higher-resolution or more recent dataset was identified, so these values were used for building the species parameters in CO2FIX.

The data show high precipitation levels for most of the year, with lower values in late spring, early summer, and September. Mean temperatures are around 6 °C in winter and reach approximately 15 °C in the summer months. Minimum monthly precipitation is 45 mm in May, while the maximum reaches about 150 mm in March.

Overall, the climate can be characterised as temperate and humid.

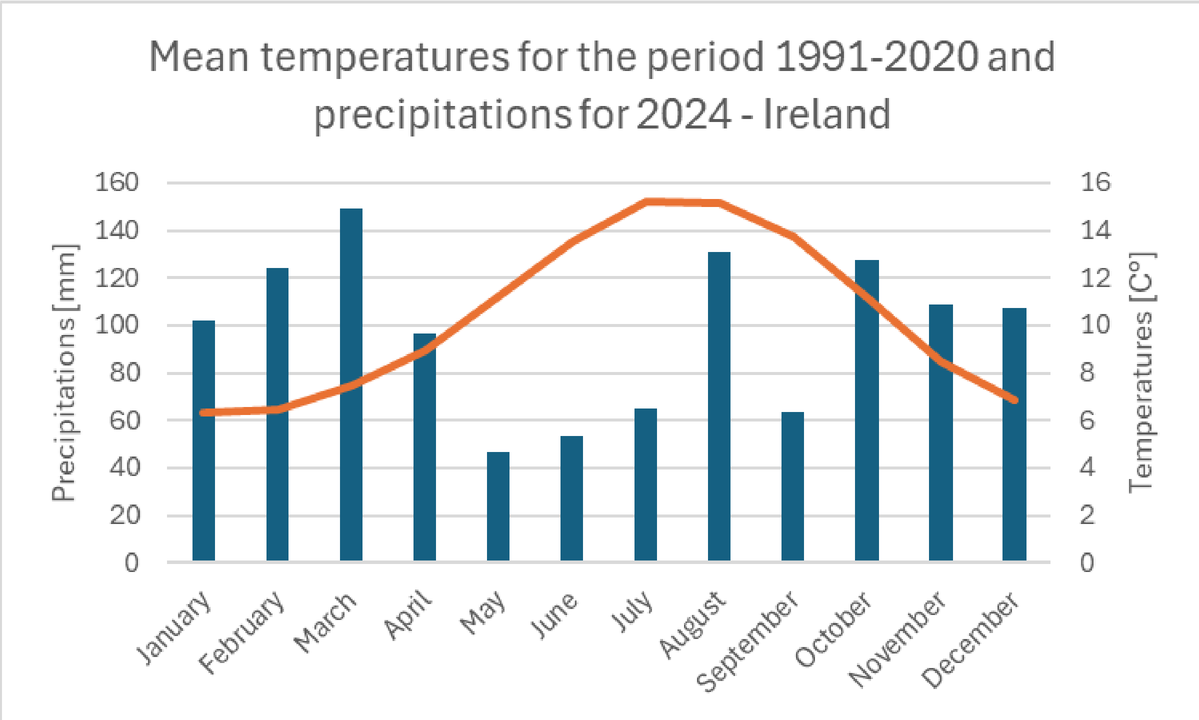

Fig. 6 *Monthly precipitations in 2024 and mean temperatures for 1991-2020 in Ireland (Deutscher Wetterdienst, 2024)*

3.9.2 Parameters for the CO2FIX Model

In the CO2FIX model, the objective is to simulate the growth of the three most prevalent tree species identified in the potential afforestation areas. Based on the map from Brus et al. (2011) (see Section 3.2), the selected species are: Black Alder (*Alnus glutinosa.*), a common alder species in Ireland; Common Oak (*Quercus robur*); and Norway Spruce (*Abies picea.*). These species represent approximately 35%, 20%, and 18%, respectively, of the species distribution in the identified potential areas.

Each species is modelled as a separate, non-competing single-species cohort, without interactions. The species models are constructed following the procedure described in Section 3.3.

Black Alder

Black alder is a short-lived broadleaved species. The rotation period typically ranges from 30 to 60 years (Horgan et al., 2003).

For the biomass module, yield tables from Claessens et al. (2010) were used. The current annual increment (CAI) was selected based on a medium yield class (Class III) in Hungary, as no more regionally relevant data were available. Since values for the first five years of growth were not provided, the model uses the mean increment value from the same table to fill this gap.

Wood density data were taken from Milch et al. (2014). The mean of the three values listed for *Alnus glutinosa* (black alder) results in a density of 0.488 MgDM/m³.

For the soil module, the monthly mean temperature values used are based on the Deutscher Wetterdienst (2025) dataset (Fig. 7). The growing season was defined as running from March to October, based on guidance from CABI (2019). The total precipitation over the course of the growing season is 732.33 mm.

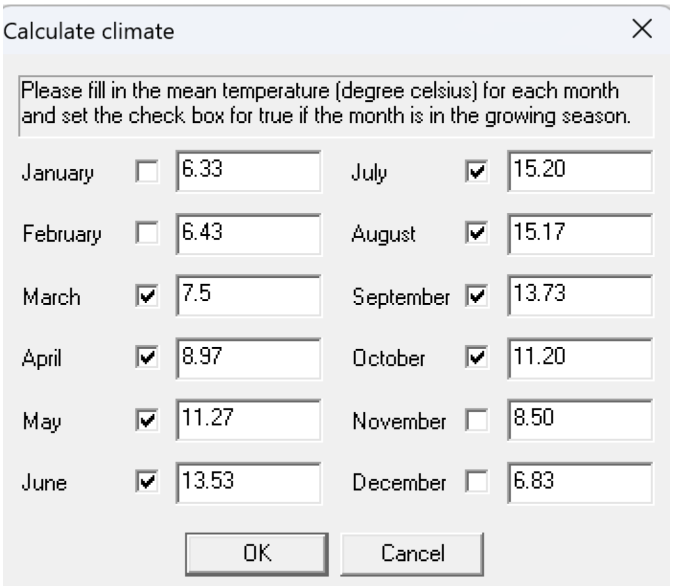

***Fig. 7** Monthly mean temperatures in Ireland and growing season for black alder*

Common oak

Common oak is a broadleaved species with a longer rotation period, typically ranging between 130 and 150 years (Horgan et al., 2003).

For the biomass module, the current annual increment (CAI) was obtained from the EFISCEN Inventory Database (Shelhaas et al., 2006). The selected yield table represents oak growth in England, as no more suitable regional data were available.

Oak wood density is based on values provided by Zachar et al. (2021), with a density of 0.681 Mg/m³.

For the soil module, the soil temperature values used are the same as those previously applied for black alder (Fig. 7). However, the growing season differs and is defined as running from April to November, based on data from Stroh et al. (2023). This results in a total precipitation of 692 mm during the growing season.

Norway spruce

Norway spruce is a coniferous and fast-growing species, with a rotation period ranging between 60 and 80 years (Horgan et al., 2003).

For the biomass module, the yield tables are taken from the EFISCEN database (Shelhaas et al., 2006) to describe the stem growth, as they were available for Ireland. The foliage, branches, and root growth, that are relative to the stem growth, are taken from the available example from the CO2FIX model.

The wood density is set at 0.440 Mg/m³, which aligns with values reported in the literature (Gryc and Horáček, 2007) and will thus be kept the same.

For the soil module, the same temperature values as in Figure 7 are used. The growing season is defined as occurring between April and October (National Biodiversity Data Centre), resulting in a total precipitation of 583.3 mm during this period (processed Section 3.2).

3.9.3 LCA parameters

Regional parameters

Parameters that need more explanation are detailed under Table 5.

Table 5 *Regional and general parameters used for the case of Ireland*

Parameters	**unit**	**Data**	**Sources**
3 Main tree species	-	Black alder, Common oak, Norway spruce	See section 3.2
meteorological data	-	Temperature mean 1990-2021, precipitation 2024	See section 3.2
share of species	% [vector]	47.95% alder, 27.4% oak, 24.65% spruce	See section 3.2
aerial management	%	0%	See section 3.2
cable management	%	29%	See section 3.2
terrestrial management	%	71%	See section 3.2

forest road density	m/ha	21.23 m/ha	Dolan et al. (2024)
forest road dimension	m2	0.225 m2	ROADEX
transport distance of seedlings	km	175 km	Dolan et al. (2024)
transport distance of gravel	km	40 km	note
transport distance of woodchips	km	107 km	Develin et al. (2016)
share of heat in the energy mix	%	66%	SEAI (2023)
share of fossil in the energy mix	%	85.8%	SEAI (2023)
seedling weight	ton	0.0005 ton (5g)	Devetakovic et al. (2019)
potential for AR	ha	5’231’700 ha	See section 3.2
time horizon	years	100 years	-

road dimension: The road dimension is based on the cross-sectional size of the gravel layer. According to ROADEX data on forest roads in Sweden, the gravelled portion is approximately 3 meters wide and 5-10 cm thick. Assuming these values are representative for Ireland, a medium thickness of 7.5 cm is used, resulting in a cross-section of 3 × 0.075 m = 0.225 m²

gravel transport: For Switzerland, an average gravel transport distance of 20 km is already included. As no country-specific data were found for Ireland, the total transport distance is assumed to be three times longer (60 km). Therefore, an additional 40 km is added to account for the difference.

woodchip transport: According to Develin et al. (2016), the transport distance for biomass in Ireland is approximately 107 km for the shorter delivery route. It is assumed that the truck does not return empty but continues with other tasks, so only one-way transport is accounted for in the analysis.

seedling transport: The transport distance for seedlings is set at 175 km, corresponding to the average distance between nursery and planting site in Ireland, as reported by Dolan et al. (2024).

Specie specific parameters

Table 6 *Tree species specific parameters used for the case of Ireland*

Parameters	Unit	Black alder	Common oak	Norway spruce
number of seedlings per hectare([9],[10],[11])	*unit*	3300	6000	2500
thinning and harvest years	*years [vector]*	scen 1: [] scen 2: [10,20,30,42,55] scen 3: every 5 years after year 10	scen 1: [] scen 2: [10,20, 30,42,54,66,81,96,111, 135] scen 3: every 5 years after year 10	scen 1: [] scen 2: [10,20,30,42,60] scen 3: every 5 years after year 10
share of biomass removed	*% [vector]*	scen 1: [] scen 2: 25% scen 3: 40%	scen 1: [] scen 2: 25% scen 3: 40%	scen 1: [] scen 2: 25% scen 3: 40%
extracted biomass	*ton/ha [vector]*	Calculated in CO2FIX for each scenario	Calculated in CO2FIX for each scenario	Calculated in CO2FIX for each scenario
number of seedlings per hectare	*years*	55	135	60
thinning and harvest years	*t/m3*	0.488	0.681	0.44

[9] Black alder: Fenessy (2004
[10] Common oak: Liziniewicz et al. (2016)
[11] Norway spruce: https://swsforestry.ie/wp-content/uploads/2016/08/NorwaySpruce.pdf

4. Results

This section presents the main results of the case study of Ireland in four parts: (1) the spatial determination of AR potential in Europe, (2) the biomass growth and carbon sequestration model (CO2FIX), (3) the life cycle assessment of project emissions and avoided emissions (Brightway25), and (4) the sensitivity analysis. Unless stated otherwise, all results are scaled to **1 hectare of forest**, and values are reported over a 100-year time horizon.

For clarity and consistency throughout the results, positive values refer to emissions (CO_2 released into the atmosphere), and negative values refer to sequestration (CO_2 captured from the atmosphere), regardless of the model or graph shown.

4.1 AR potential in Europe

This section gives a quick overview of the results regarding AR potential across European countries. Based on the map produced (see Section 3.2), we identify which areas are suitable for AR. Each white pixel on the map represents a 1000 x 1000 m2, or 100 ha.

According to the map, the three countries with the largest total AR potential are:

- **France**: 14’943’000 ha (≈23% of the national territory)
- **Spain**: 12’435’100 ha (≈25%)
- **United Kingdom**: 9’303’900 ha (≈39%)

However, when looking at AR potential relative to total country area, the top three countries change:

- **Ireland**: 5’231’700 ha (≈76%)
- **Portugal**: 4’256’200 ha (≈47%)
- **Greece**: 6’032’700 ha (≈46%)

Based on this high relative potential, Ireland was selected as the focus for the case study, and the following chapters describe the results for this specific case.

4.2 Carbon dynamics from CO2FIX model

Here are presented the results from the model CO2FIX for the case of Ireland, thus the results of the three main species defined earlier: Black alder, Common oak, and Norway spruce. The models were run over a time horizon of 450 years to allow for the extension of the life cycle assessment (LCA) and to observe long-term growth patterns. However, only the first 200 years are shown here, as the trends tend to repeat beyond that point, and this is also the maximum time frame considered in the assessment.

Three different forest management scenarios were tested: no management, moderate management, and intensive management. These scenarios influence biomass growth and carbon sequestration outcomes. The following section presents the results for:

- Biomass carbon storage (in tC/ha),
- Soil carbon storage (in tC/ha), and
- Total carbon storage (in tC/ha).

As the goal is to compare different management strategies on biomass, the following graphs show, for each species (Black alder, Common oak, Norway spruce), how biomass evolves over time depending on the chosen scenario. In the following graphs, biomass includes both above- and belowground elements (foliage, branches, stems, roots).

4.2.1 Biomass carbon sequestration

Black Alder (Fig. 8)

Scenario 1 shows a relatively fast increase in biomass, reaching a plateau around year 80 at approximately 123 tC/ha. After that, it remains stable for a while before slowly declining, probably due to natural mortality.

Scenario 2 shows repeated drops in biomass corresponding to thinning events. The biomass peaks around 90 tC/ha before final harvesting, after which the cycle restarts.

Scenario 3 presents more and smaller ups and downs due to more frequent thinning, and also shows much lower overall biomass accumulation, with a maximum around 31 tC/ha. From around year 34 onward, a slight declining trend is noticeable and repeated through the rotation.

Overall, Black Alder under no management allows for the greatest long-term biomass accumulation. Scenario 2 maintains a relatively high average biomass despite periodic thinning, while scenario 3 severely limits biomass accumulation.

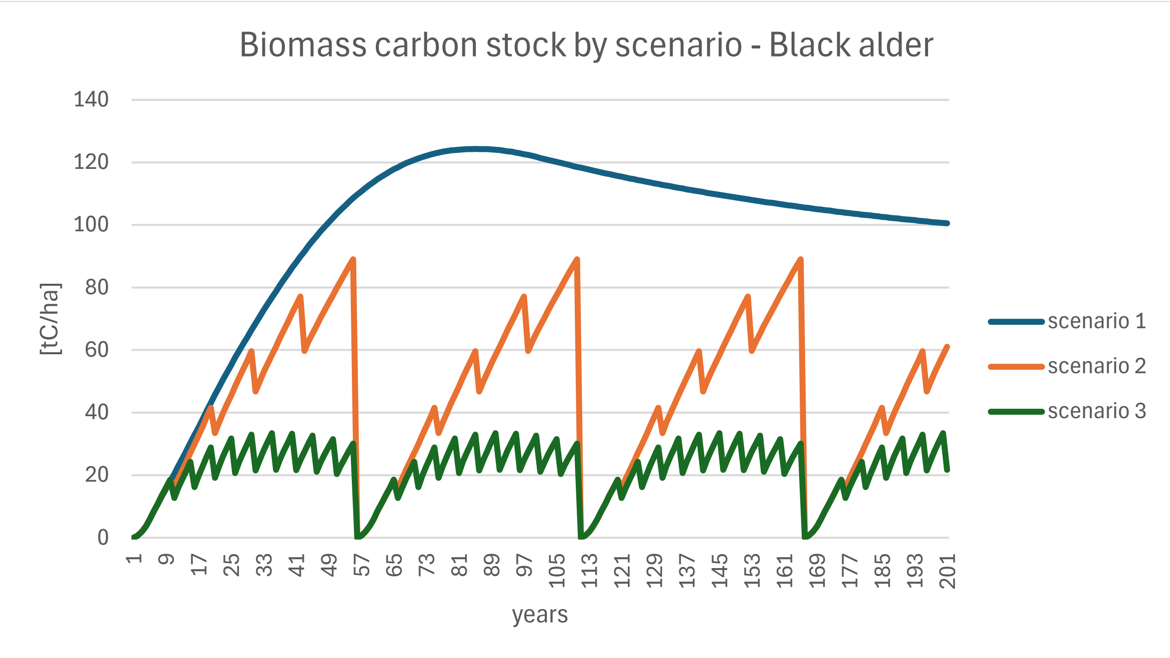

Fig. 8 *Biomass carbon stock by scenario over 200 years in [t C/ha] - Black alder*

Common Oak (Fig. 9)

Similarly to Black alder, scenario 1 leads to a fast increase in biomass, peaking close to 120 tC/ha around year 90, followed by a decline that seems steeper than what was observed for the previous species.

Scenario 2 shows very rapid growth with a peak around 91 tC/ha at year 80, but begins to decline very slightly after this.

Scenario 3 leads to much lower biomass accumulation, peaking around 33 tC/ha at year 45 and then decreasing slowly until the end of the rotation period.

Scenario 1 clearly retains the most biomass, although the decline after the peak is more pronounced than in scenario 2. Scenario 3 remains far below in terms of accumulation.

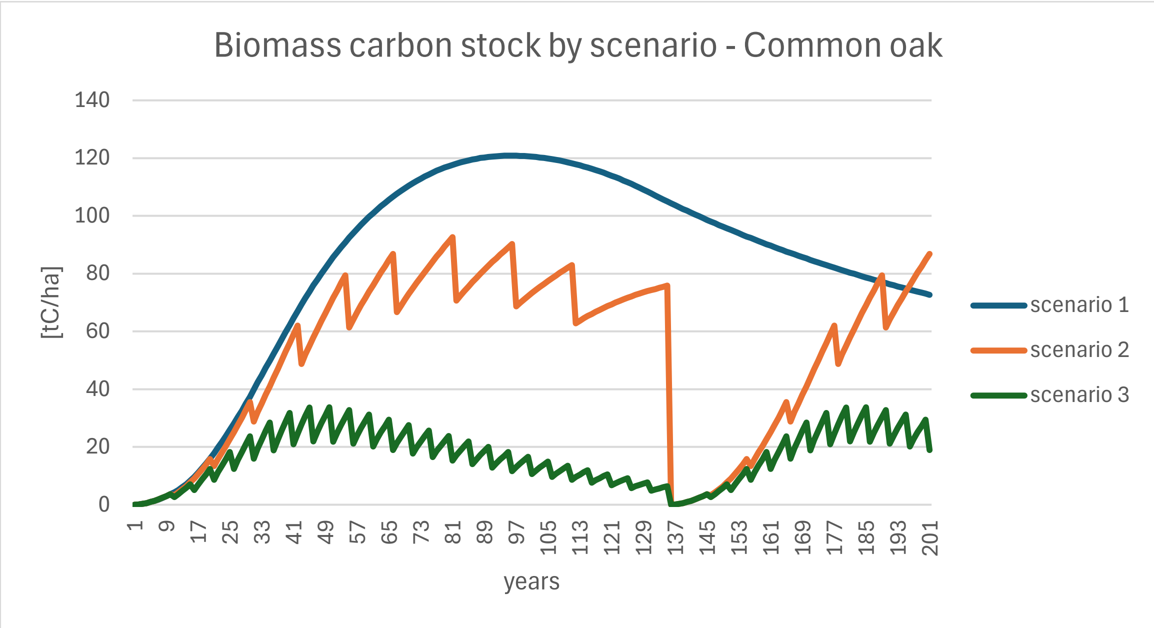

Fig. 9 *Biomass carbon stock by scenario over 200 years in [t C/ha] - Common oak*

Norway Spruce (Fig. 10)

Scenario 1 shows biomass accumulation reaching nearly 240 tC/ha, after which the curve flattens out, suggesting growth stabilization.

Scenario 2 also shows rapid growth, peaking around 194 tC/ha by year 41. Although growth slows down afterwards, no decline is observed during the rotation period.

Scenario 3 peaks around 107 tC/ha at year 30 and then shows a gradual decline until final harvesting.

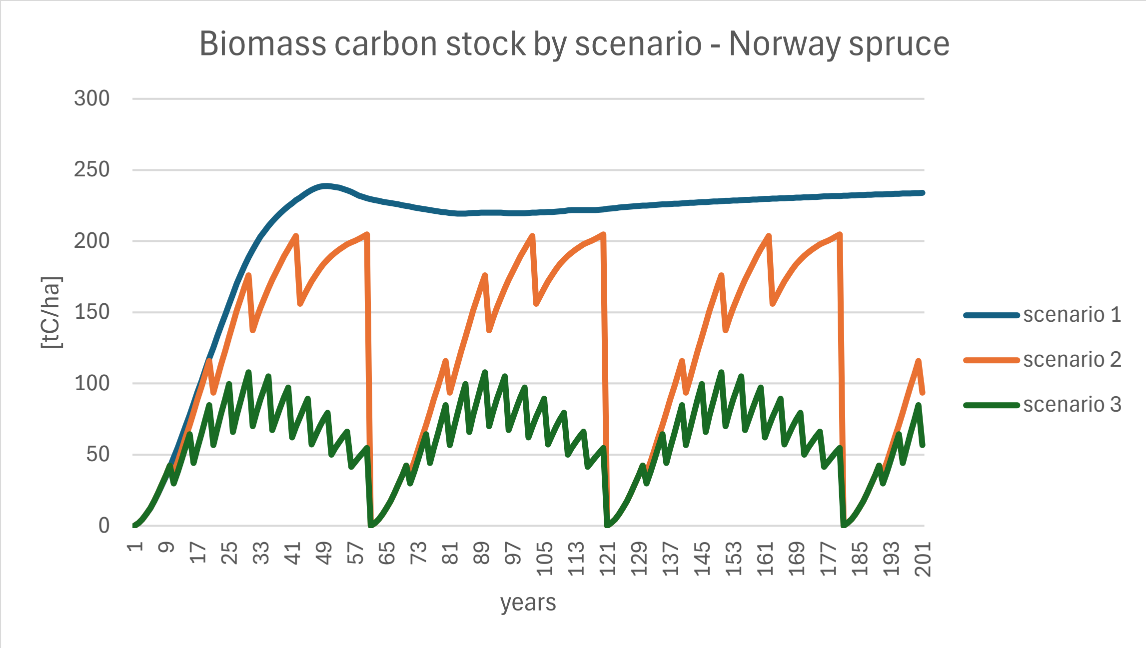

Fig. 10 *Biomass carbon stock by scenario over 200 years in [t C/ha] - Norway spruce*

Summary

In general, the scenario with no thinning (scenario 1) results in rapid early growth and leads to the highest cumulative biomass. After the plateau is reached, the growth either stabilizes or declines slightly, but no biomass is extracted. In contrast, scenarios 2 and 3 involve thinning events, which remove part of the biomass regularly, leading to lower total accumulation. Scenario 3 in particular limits biomass growth significantly, due to frequent removals that prevent the forest from developing further. These results clearly show that the management regime plays a major role in shaping the biomass carbon storage potential of a forest.

4.2.2 Soil carbon sequestration

The graphs below illustrate the cumulative soil carbon storage (in tC/ha) over 200 years for each species under the three different management scenarios. As with biomass, we observe distinct trends in soil carbon dynamics depending on both the species and the management intensity.

Black alder (Fig. 11)

Scenario 1 shows a steady accumulation of soil carbon, reaching a plateau around 25 tC/ha after year 80, and remaining relatively stable afterwards.

In Scenario 2, soil carbon accumulation occurs more slowly and generally remains well below the levels observed in Scenario 1. Final harvesting events are clearly visible as sharp peaks reaching up to approximately 27 tC/ha, followed by steep declines.

Scenario 3 follows a similar pattern but with lower peaks (~15 tC/ha) and more frequent fluctuations due to heavier thinning operations

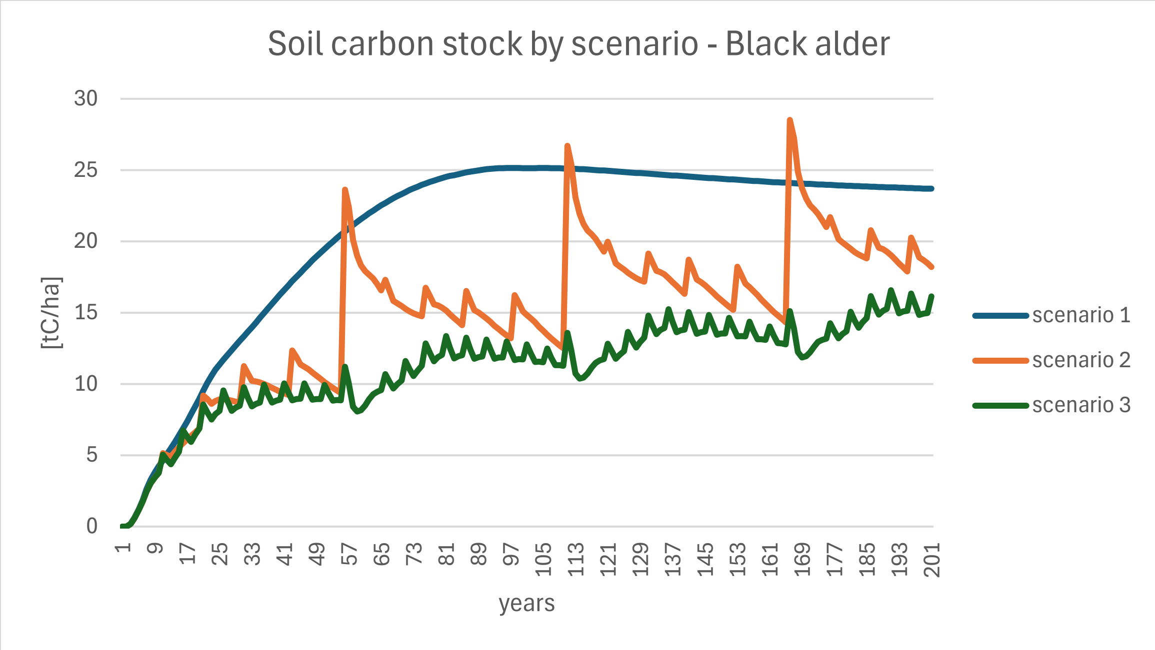

Fig. 11 Soil carbon stock by scenario over 200 years in [t C/ha] - Black alder

Common oak (Fig. 12)

In Scenario 1, soil carbon builds up slowly and steadily to about 25 tC/ha with a maximum around year 100, followed by a mild decline.

Scenario 2 shows more variability, with periodic spikes and drops that align with thinning cycles, including one large peak (~16 tC/ha) around year 135. Disregarding the spike following final felling, soil carbon storage remains generaly between 7 and 15 tC/ha.

Scenario 3 shows similar soil carbon storage levels to Scenario 2, but with more frequent thinning operations, leading to greater variability, though with smaller magnitude. This can be explained by less biomass being left in the forest to be absorbed in the soil. No distinct peak is observed at the time of final harvest, and values generally remain between 5 and 10 tC/ha.

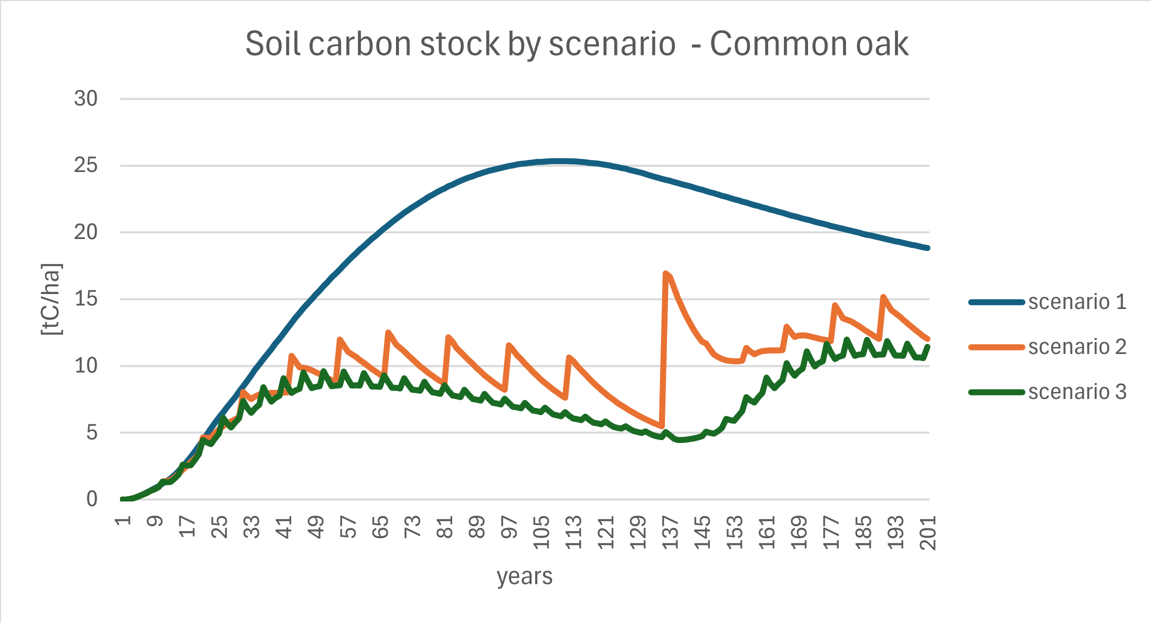

Fig. 12 *Soil carbon stock by scenario over 200 years in [t C/ha] - Common oak*

Norway spruce (Fig. 13)

Scenario 1 presents the slowest and steadiest increase in soil carbon, rising gradually to about 70 tC/ha by year 200.

Scenario 2 again shows sharp peaks and drops in soil carbon, reaching up to 90 tC/ha, driven by thinning operations and the final felling. Aside from the final harvest peak, values generally range between 25 and 55 tC/ha, with a slight upward trend over time.

Scenario 3 presents similar patterns, though with smaller fluctuations and slightly lower values overall, typically between 15 and 40 tC/ha. Here too, a modest increasing trend can be observed over the time horizon.

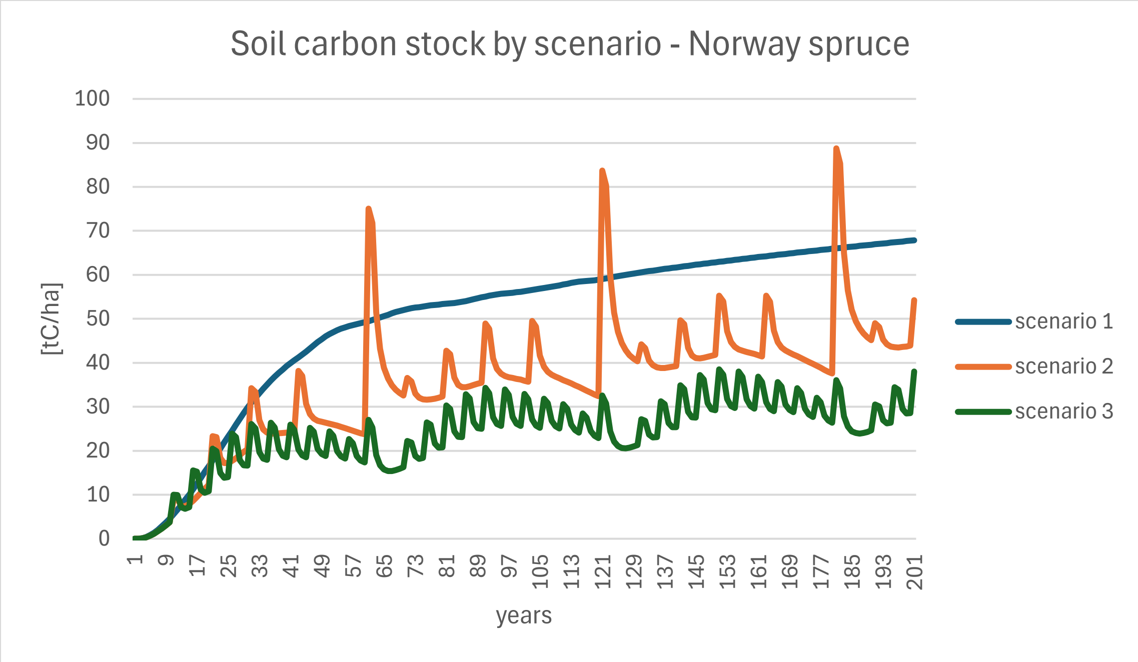

Fig. 13 *Soil carbon stock by scenario over 200 years in [t C/ha] - Norway spruce*

Summary

Again, Norway spruce stands out with roughly double the soil carbon storage compared to the other two species, across all scenarios. This is likely due to its much higher biomass, which contributes more residues and organic matter to the soil.

Overall, Scenario 1 leads to the highest soil carbon storage across all species over the 200-year timeframe, although it tends to plateau or decline slightly toward the end. In Scenario 2, sharp peaks in soil carbon are observed at the time of final felling, likely because thinning operations remove relatively little biomass, while final harvesting leaves a much larger amount in the forest. Additionally, 15% of the biomass removed during thinning is left onsite and contributes to soil carbon, whereas in Scenario 3, only 5% remains, limiting the soil sequestration potential. However, Scenario 3 involves more frequent and heavier thinning, which distributes amounts of biomass into the soil that are less contrasting with the final harvest.

4.2.3 Total carbon sequestration (biomass and soil)

The following graphs show the total carbon sequestration over time for each species (Black alder, Common oak, and Norway spruce), combining both biomass and soil carbon stocks for a 200 years' time horizon. These results allow for a clearer view of the overall carbon storage potential under different forest management strategies. As before, the three scenarios correspond to no management (scenario 1), moderate thinning (scenario 2), and intense thinning (scenario 3).

Given that the proportion of biomass incorporated into the soil is relatively low (15% in Scenario 2 and 5% in Scenario 3), soil carbon storage is not expected to have a strong influence on total carbon storage. As a result, the graphs are anticipated to show patterns similar to those observed for biomass carbon storage.

Black alder (Fig. 14)

Scenario 1 shows a quick increase in carbon sequestration, reaching around 150 tC/ha at year 80, after which it stabilizes and slowly declines to 120 tC/ha at the end of the time horizon.

Scenario 2 shows repeated growth and drops due to harvesting, reaching ~100 tC/ha during peaks. A very light increasing trend can be observed.

Scenario 3 accumulates the least carbon, staying below 50 tC/ha with more frequent but smaller fluctuations. A very light increasing trend can also be observed.

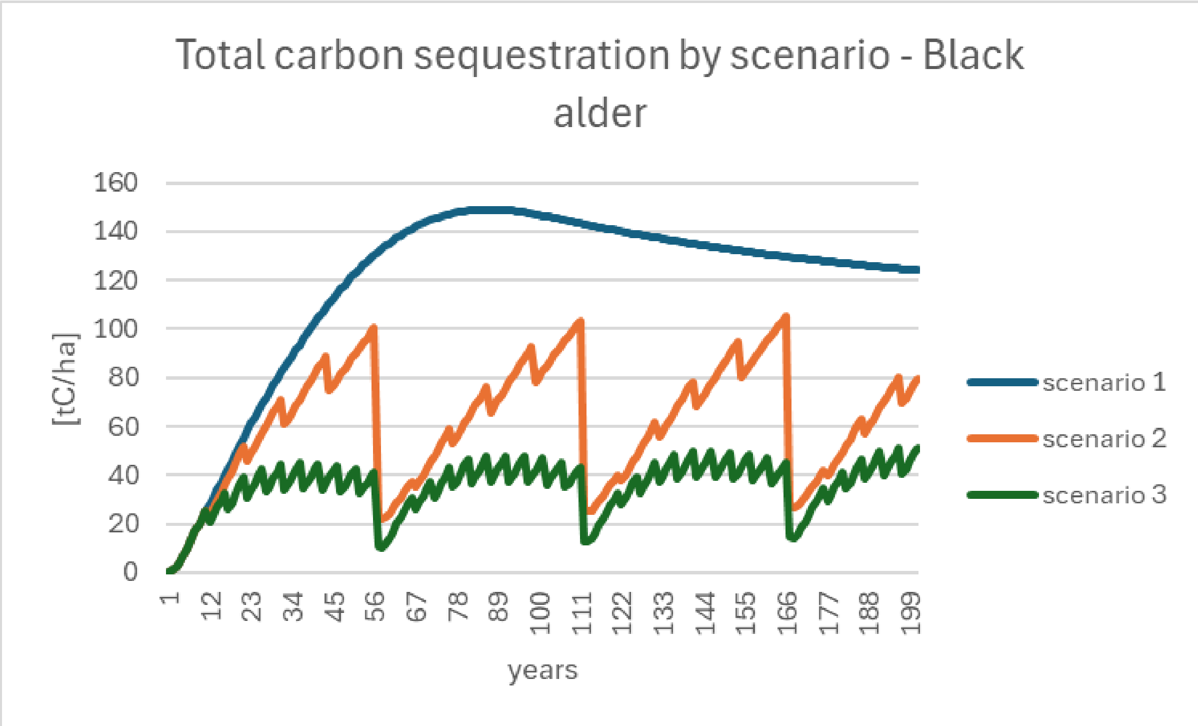

Fig. 14 *Total carbon sequestration by scenario over 200 years in [t C/ha] - Black alder*

Common oak (Fig. 15)

Scenario 1 leads to a peak around 145 tC/ha at year 85, followed by a clear and steady decline to around 90 tC/ha.

Scenario 2 follows a similar trajectory at first, but reaches a lower maximum (~105 tC/ha at year 80). The end of the rotation period of 135 years shows a strong drop, before going back up again on what seems to be the same pattern.

Scenario 3 remains well below the other two, with values ranging between 5 and 45 tC/ha depending on the phase of the cycle.

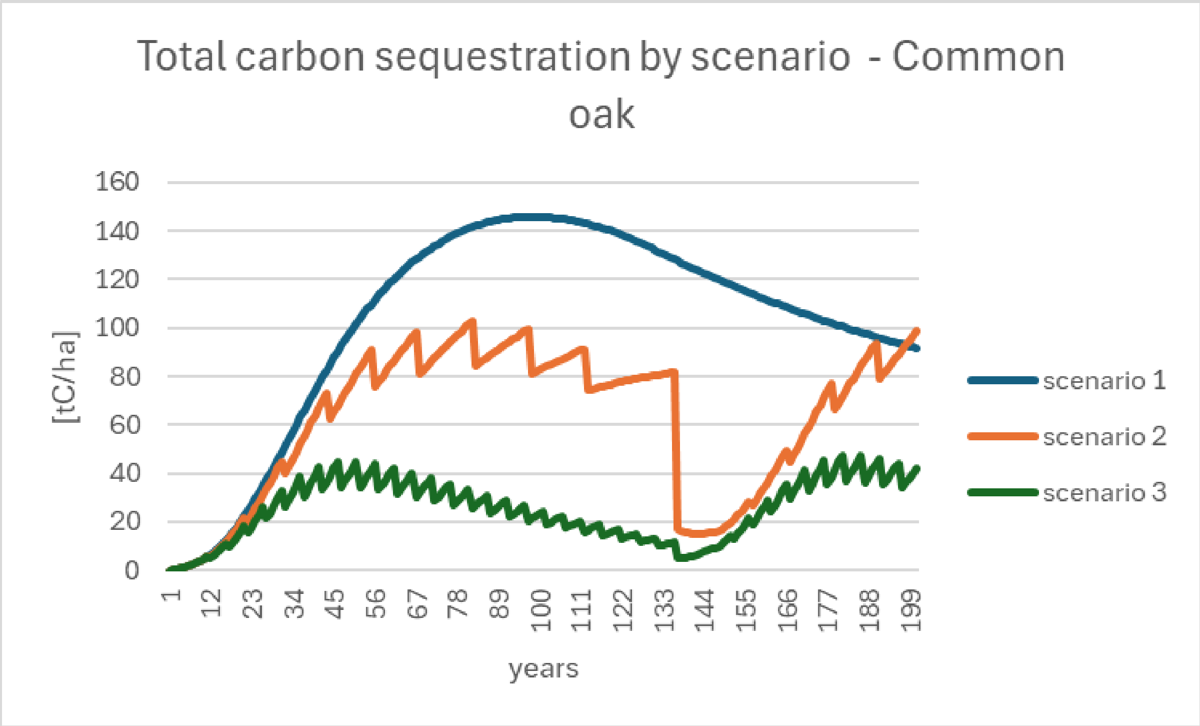

Fig. 15 *Total carbon sequestration by scenario over 200 years in [t C/ha] - Common oak*

Norway spruce (Fig. 16)

Total sequestration is significantly higher for Norway spruce.

Scenario 1 shows a fast accumulation, levelling out at around 280 tC/ha at year 50, followed by a steady and slightly upward trend.

Scenario 2 reaches lower levels, with peaks close 250 tC/ha during each cycle, and lows around 50 tC/ha. A very slight increasing trend can be observed.

Scenario 3 accumulates less but still reaches around 140 tC/ha and with smaller variations between highs and lows. A very slight increasing trend can also be observed.

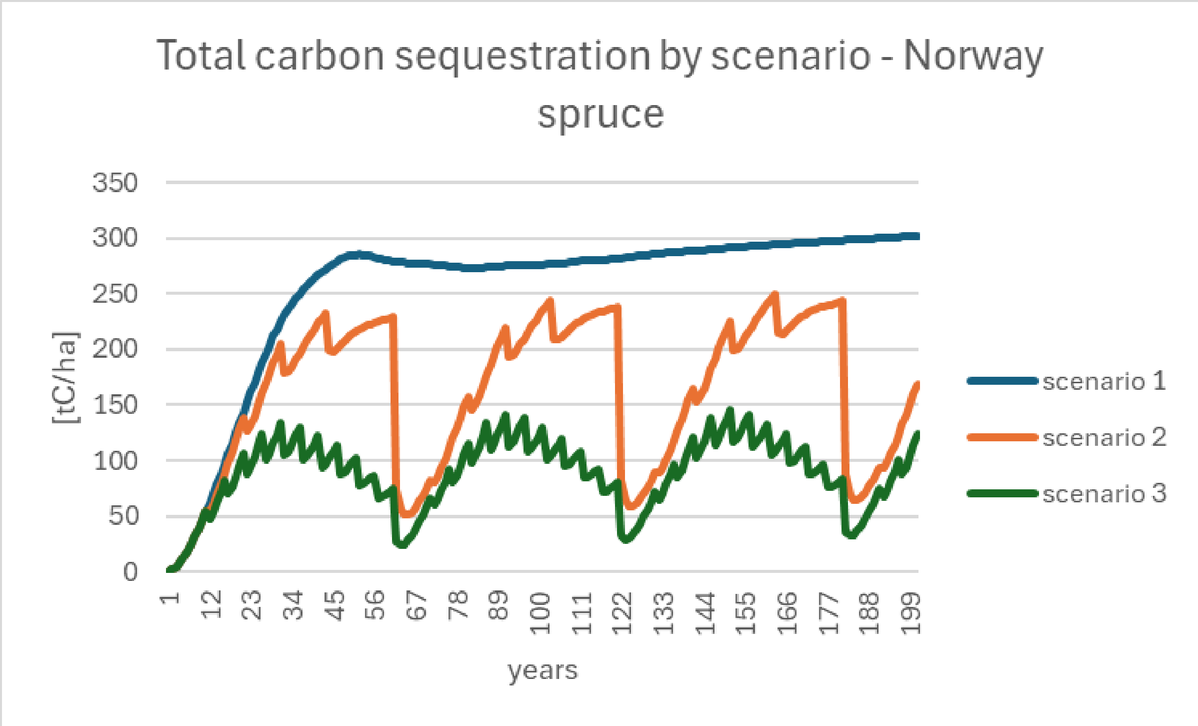

Fig. 16 *Total carbon sequestration by scenario over 200 years in [t C/ha] - Norway Spruce*

Summary

Norway spruce clearly outperforms the other species in total carbon storage under all scenarios, sequestering roughly twice as much carbon. Several factors may explain this result, and they are discussed later in the discussion section.

Scenario 1 consistently stores the most carbon over the long term, although it is the least dynamic. Scenario 2 shows good performance, while Scenario 3 limits total sequestration across all species due to frequent and intensive thinning.

The differences between scenarios clearly underline how important the choice of management regime is when implementing AR as a strategy to reduce atmospheric carbon.

4.2.4 Summary of carbon sequestration rates

To facilitate comparison with literature values, which are often reported as sequestration per year over fixed time horizons, the average annual carbon sequestration rates were calculated over both the full 100-year time horizon and the first 20 years following plantation. These results, summarized in Table 7, enable comparison across species and scenarios, as well as with published studies.

Table 7 *Mean annual carbon sequestration from the forest growth model (CO2FIX) per scenario and species, averaged over 0–20 years and 0–100 years in [tCO_2-eq/ha/year]*

	Black alder (100-yr)	**Common oak (100-yr)**	**Norway spruce (100-yr)**	**Black alder (20 yr)**	**Common oak (20 yr)**	**Norway spruce (20 yr)**	**All species (100-yr)**	**All species (20 yr)**
scen 1	5.32	5.29	10.03	10.68	4.52	27.9	6.47	13.24
scen 2	8.90	6.70	20.0	10.82	4.56	28.54	11.03	13.48
scen 3	9.56	7.02	23.26	10.89	4.6	28.0	12.24	13.39

4.3 Project emissions (LCA results)

This section presents the results of the LCA part of the project for the case of Ireland, based on the parameters described in Section 3.5. All values are expressed in kg CO_2-equivalent, and the calculations are made per hectare of reforested area.

Since each tree species has different requirements, such as the number of seedlings or the length of the rotation period, it was necessary to perform a separate LCA for each species. Therefore, for every management scenario, three LCA models were created (one per species). As the results are relatively similar across species, only the graphs and results for the most common one (Black alder) are shown here. The full set of LCA results for the other species can be found in Appendix C..

For each scenario, two graphs are presented: one showing cumulative emissions by activity, and another detailing annual emissions over time, with each activity clearly distinguished.

To facilitate comparison and interpretation, Table 8 summarises cumulative positive emissions, negative emissions, and the resulting net balance for each species across the three scenarios. While most results in the section 4.3 are presented in kg CO_2-eq/ha (as this is the default output of the LCA model), summary tables or final overview, including Table 8, use tCO_2-eq/ha for easier readability.

In this study, carbon sequestration is represented as a negative value (removals from the atmosphere), while emissions are positive. Therefore, the net carbon balance is calculated as:

Net balance = Emissions + Sequestration

A positive net balance indicates that the project results in net greenhouse gas emissions, while a negative value reflects a net carbon sink.

Table 8 *Summary of cumulative positive emissions, negative emissions, and net balance [tCO$_2$-eq/ha] for all species and scenarios*

	scenario 1			**scenario 2**			**scenario 3**		
	spe1	**spe2**	**spe3**	**spe1**	**spe2**	**spe3**	**spe1**	**spe2**	**spe3**
Positive emissions	0.19	0.26	0.17	13.67	10.06	25.01	19.14	17.31	42.98
Negative emissions	0	0	0	-40.60	-25.22	-78.90	-57.28	-43.85	-136.31
Net balance	0.19	0.26	0.17	-26.93	-15.16	-53.90	-38.14	-26.54	-93.33

4.3.1 Scenario 1 (no management):

In this scenario, the site is prepared and the forest is planted in year 0, with no further interventions throughout the entire time horizon.

Cumulative emissions by activity

In Figure 17, the two first lines represent the total positive and negative emissions. Since no energy substitution occurs in the first scenario, there are no negative emissions. The total positive emissions (and also net balance) amounts to approximately 190 kgCO$_2$-eq/ha. The two main contributors are the seedlings and the planting activity, which together account for over 160 kgCO$_2$-eq/ha, while all other activities generate only minimal emissions by comparison (< 20 kgCO$_2$-eq/ha).

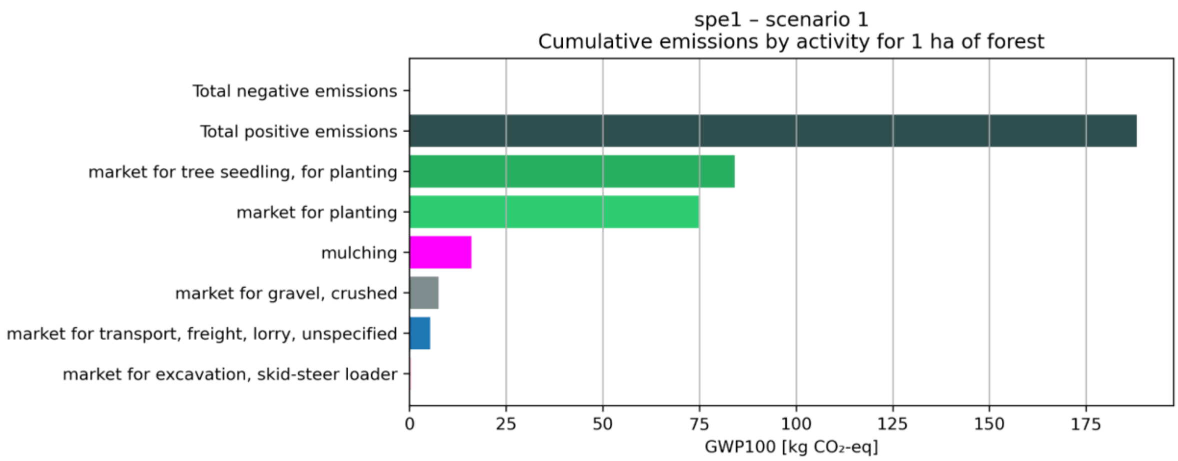

Fig. 17 *Cumulative emissions by activity for 1 ha over 100 years in [kgCO$_2$-eq/ha] - scenario 1, specie 1*

Yearly emissions by activity

As the graph (Fig. 18) shows the yearly emissions broken down by activity, and in this scenario all activities occur in the first year, only a single bar is visible. As a result, the graph provides little additional insight beyond confirming that emissions are concentrated entirely at the beginning of the project.

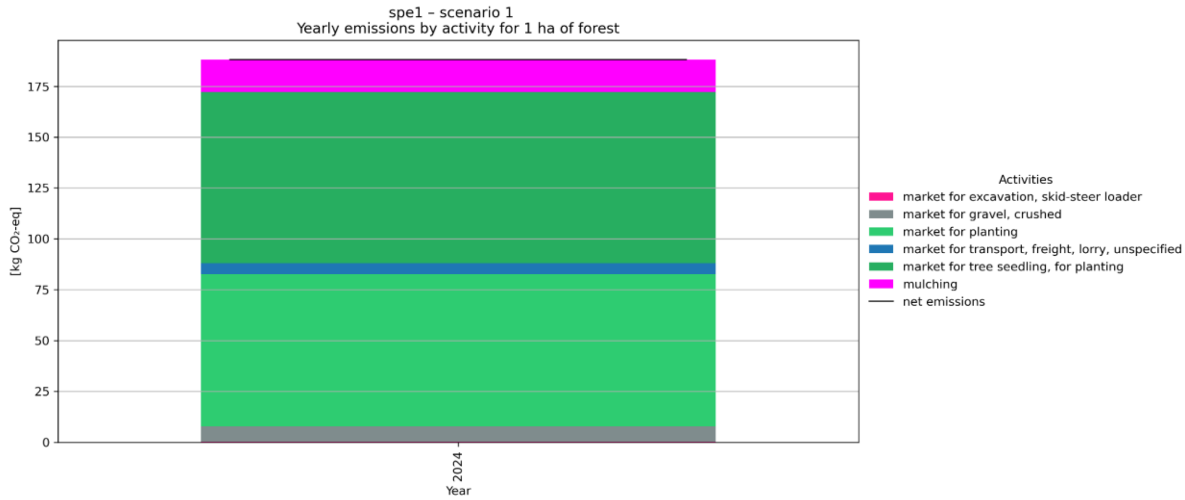

***Fig. 18** Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 1, specie 1*

Scenario 1 results in very low positive emissions associated with the establishment of the forest, which are negligible compared to the carbon sequestration provided over time as seen in Section 4.2. Common oak performs slightly worse, at 260 kgCO_2-eq/ha, due to nearly double the number of seedlings planted, while Norway spruce shows similar results to the first species, with 170 kgCO_2-eq/ha.

4.3.2 Scenario 2 (moderate management):

In this scenario, the site is prepared and the forest is planted at year 0, as well as replanted after the end of the rotation period. Moderate thinning is carried out at regular intervals until the final harvest at the end of the rotation period.

Cumulative emissions by activity

The first graph (Fig. 19) for scenario 2 shows, in the first two bars, substantially higher negative emissions (-40’597 kgCO_2-eq/ha) compared to positive emissions (13’668 kgCO_2-eq/ha). These values are on a completely different scale from those in scenario 1. This difference is explained by the fact that, unlike scenario 1, where almost no activities take place, scenario 2 includes regular forest interventions and material transport. These operations generate more emissions, but they also enable greater substitution benefits by replacing fossil energy with bio energy.

On the positive emissions side, two activities dominate: energy production from woodchips (6’443 kgCO_2-eq/ha) and cable yarding (5’154 kgCO_2-eq/ha, used for cable management). This is particularly notable given that 71 % of the forest operations are terrestrial, and the skidder (used for terrestrial management) produces roughly ten times fewer emissions. Overall, transport, wood chipping, and skidder operations contribute relatively little, around 500-650 kgCO_2-eq/ha each, and all other activities are negligible in terms of emissions (<160 kgCO_2-eq/ha), barely visible on the graph.

On the negative emissions side, the largest contribution comes from the substitution of electricity (-31’846 kgCO_2-eq/ha), followed by the substitution of heat from fossil sources (-8’750 kgCO_2-eq/ha). Both provide a strong offsetting effect, significantly reducing the net emissions. As a result, this scenario achieves a net balance of -26’930 kgCO_2-eq/ha, even before accounting for carbon sequestration from biomass growth.

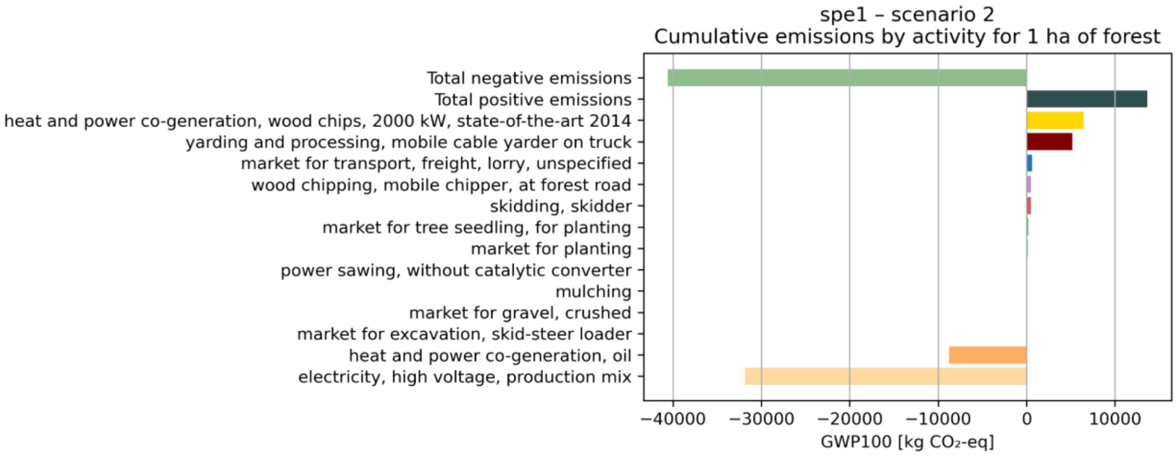

Fig. 19 *Cumulative emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 2, specie 1*

Yearly emissions by activity

The second graph (Fig. 20), which shows the temporal distribution of emissions per activity, highlights recurring emission spikes during thinning operations, with a major peak at year 55 (2079) corresponding to the final harvesting event. In that year, most emissions come from cable yarding and energy production using woodchips, while transport and other machinery contribute only marginally, consistent with the results from the previous graph. Negative emissions are particularly high in this year, more than offsetting the positives, as reflected in the net balance line, which sits at around -12’886 kgCO_2-eq/ha.

In the first year (or the first year after final felling), emissions are mainly from planting (~160 kgCO_2-eq/ha), with no negative emissions. Each year with thinning operations shows simultaneous increases in both positive and negative emissions, with the net balance improving from approximately -690 to -2’800 kgCO_2-eq/ha over time. This trend occurs because the thinning amount is calculated as a percentage of the growing biomass; as biomass increases, the scale of forest management operations also grows. The activity shares during thinning years follow the same proportions observed in the final harvesting year. Importantly, in every year with thinning activity, the net emissions remain negative, meaning that the substitution benefits consistently outweigh the generated emissions.

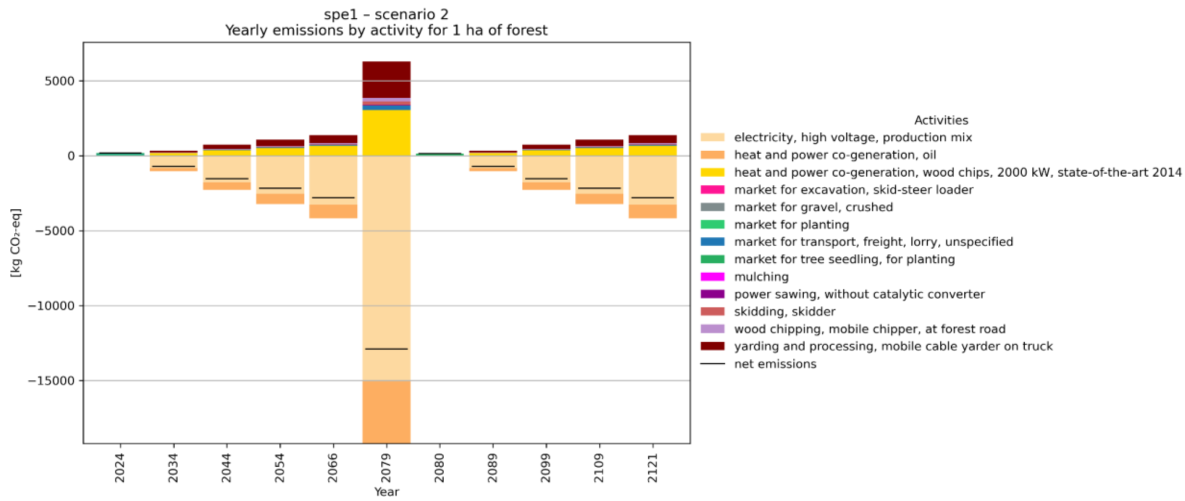

Fig. 20 *Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 2, specie 1*

Summary

Compared to scenario 1, scenario 2 produces significantly higher emissions due to more frequent interventions. However, these interventions also enable greater substitution of fossil energy through the periodic removal and use of biomass, resulting in an overall net negative emission outcome. In this case, increased forest management leads to both higher emissions and greater avoided emissions through energy substitution. The other two species show similar trends. For the second species (common oak), which has a longer rotation period, the yearly emissions pattern differs slightly: planting occurs only once, and the final felling falls outside the assessed time horizon. This explains why total negative emissions (-25’223 kgCO_2-eq/ha), while still sufficient to offset the positives (10’064 kgCO_2-eq/ha), are lower , as the final harvest does not take place within the assessment period. For the third species (Norway spruce), the graphs follow a similar pattern to the first species but, as highlighted earlier in the CO2FIX results, twice as much biomass is produced. This results in greater management needs and, consequently, roughly double the negative and positive emissions compared to the first species (-78’903 and 25’006 kgCO_2-eq/ha respectively).

4.3.3 Scenario 3 (heavy management):

In this scenario, the site is prepared and the forest is planted at year 0, and again after the end of the rotation period. Intensive management takes place every five years until the final harvest at the end of the rotation cycle.

Cumulative emissions by activity

In the first graph (Fig. 21), both positive (19’144 kgCO_2-eq/ha) and negative (-57’282 kgCO_2-eq/ha) emissions are higher than in scenario 2. This results in a net balance that is more favorable in terms of sequestration. Overall, the graph maintains a similar structure, with the same activities contributing proportionally to total emissions. The higher values observed here are likely due to more frequent thinning operations, which process smaller quantities of biomass per intervention but occur more often, therefore leading to more energy substitution.

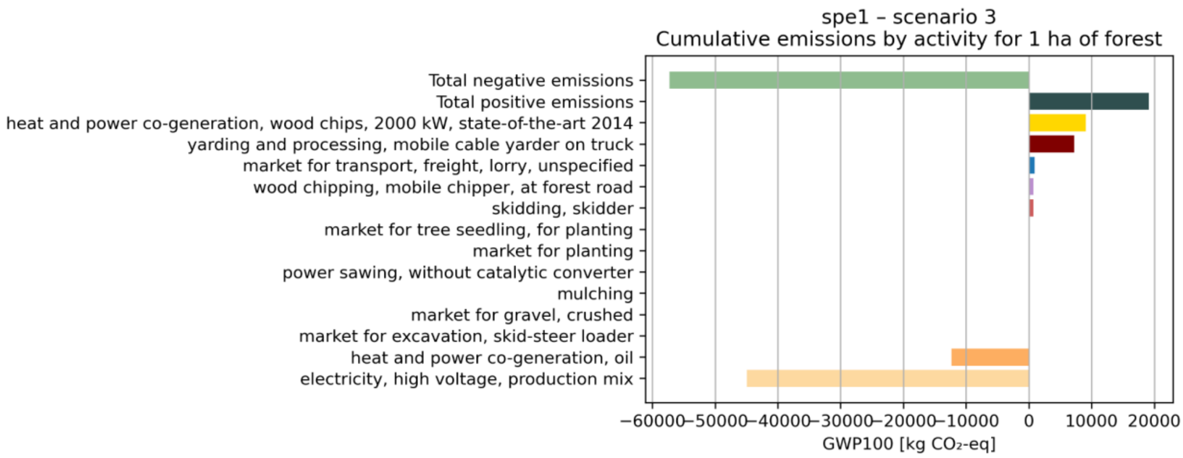

***Fig. 21** Cumulative emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 2, specie 1*

Yearly emissions by activity

In the second graph (Fig. 22), emissions are more evenly distributed over time due to the increased frequency of thinning operations, resulting in regular and relatively consistent emission levels. During thinning years, the net balance ranges from a low of around -1'240 kgCO_2-eq/ha to most years averaging about -2'200 kgCO_2-eq/ha, while the final harvest year reaches a net balance of -5'012 kgCO_2-eq/ha.

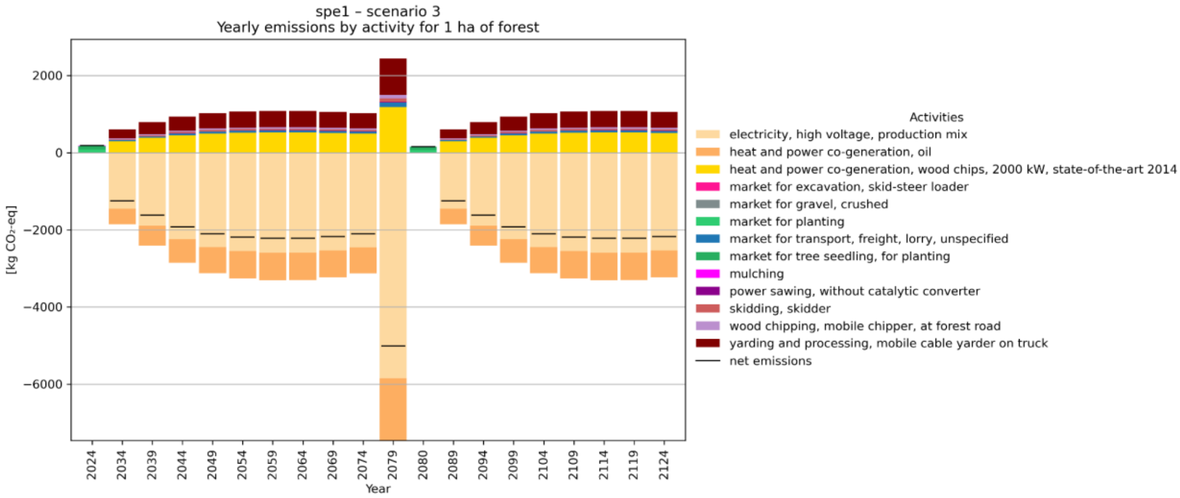

***Fig. 22** Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 3, specie 1*

Summary

Management-related emissions are strongly influenced by the amount of biomass processed. In scenario 3, although less biomass is processed per intervention, operations occur more frequently, resulting in greater negative emissions over time compared to scenario 2. Black alder achieves a net balance of -38’140 kgCO$_2$-eq/ha, while common oak shows less negative emissions (-26’540 kgCO$_2$-eq/ha) as the final harvest falls outside the time horizon. Norway spruce once again records significantly higher values, reaching a net balance of -99’330 kgCO$_2$-eq/ha.

4.3.4 Comparison across scenarios

The comparison of the three scenarios highlights how forest management intensity directly influences both the distribution and timing of emissions over the project’s life cycle. Scenario 1, with no management after planting, concentrates all emissions in the first year and provides no negative emissions from energy substitution. Scenario 2, with moderate interventions and a final harvest, produces more emissions overall but also delivers substantial substitution of fossil fuels with biomass, resulting in greater net climate benefits. Scenario 3, characterized by more frequent interventions, generates higher emissions but also achieves higher substitution benefits, leading to the most favorable overall outcome in terms of net emissions.

From a life cycle assessment perspective, intensive management, as in scenario 3, appears to offer the best trade-off between intervention intensity and climate benefit. These results highlight the significant role that management style plays in determining the emissions associated with forest operations.

4.4 Net climate impact and regional potential

Net climate impact

To evaluate the net climate impact of a forest, data from all components were combined and harmonized to express results in tonnes of CO$_2$-equivalent (tCO$_2$-eq) for an hectare of forest, ensuring comparability across processes. From this point onward, the three species previously analysed separately are combined into a mixed forest, using the share of species defined in Section 3.9.3 for the case study. Table 9 summarizes the results.

Table 9 *Summary of project emissions (net and positive for the LCA), sequestration (seq.), and net climate balance, mean annual seq. rate, and share of positive emissions relative to the net balance, for each main scenario over 100 years, in tCO$_2$-eq/ha if not specified otherwise*

	Project net emissions (LCA)	**Project positive emissions (LCA)**	**Seq. (CO2FIX)**	**Net climate balance**	**Annual seq. rate (tCO$_2$-eq/ha/yr)**	**Positive emissions as % of net climate balance (%)**
Scen 1	0.20	0.20	-653.63	-653.43	-6.47	0.03%
Scen 2	-30.35	15.48	-1114.37	-1144.73	-11.36	1.35%
Scen 3	-48.57	24.52	-1236.21	-1284.77	-12.76	1.91%

Figure 23 presents the cumulative emissions, carbon sequestration, and net climate effect over a 100-year period for three forest management scenarios. The y-axis shows cumulative impacts in tCO_2-eq/ha for one hectare of forest, where negative values indicate a climate benefit (emissions sequestration). The x-axis represents time, from year 0 to year 100.

Each scenario is shown in a different color, with three lines: emissions from the project (LCA) are represented with a dashed line, carbon sequestration from the forest model (CO2FIX) with a dotted line, and the resulting net balance with a solid line.

Scenario 1 (green) shows a rapid sequestration in the first years, which slows down gradually before reaching a plateau during the last years. As all emissions occur in the first year and are very small compared to the total sequestration, it does not really show on the graph. The mean emissions from the project over the time horizon is 0, and so the dashed line is mixed with the axis. By year 100, this scenario results in -653 tCO_2-eq/ha sequestered per hectare.

Scenario 2 (blue) follows a similar trend as scenario 1 during the first 25 years. Between years 25 and 60, sequestration slows slightly, as older forests capture less carbon, but remains higher than in scenario 1. By year 60, two species have reached the end of their rotation period, leading to activities that result in a large amount of CO_2-eq/ha being sequestered. After replanting, the forest restarts from zero, allowing for more rapid sequestration once again. The LCA part remains very close to the zero axis. By the end of the time period, -1’144 tCO_2-eq/ha has been sequestered in total per hectare of forest.

Scenario 3 (red) follows a similar trend to the other scenarios during the first 25 years and keeps a steeper sequestration slope indicating higher carbon uptake. Sequestration gradually slows over time until around years 55 to 60, when both rotation periods end. During this interval, sequestration drops due to emissions from management activities, before increasing again as new trees are planted for two species. The LCA component also shows higher sequestration than in the other two scenarios, although it remains small compared to the contribution from trees. By the end of the time period, -1’284 tCO_2-eq/ha has been sequestered per hectare.

Across all scenarios, the negative emissions from the forest project (LCA) are visible on the graph but remain close to the zero axis, representing less than 2% of total sequestration over the time horizon. The results indicate that the management regime influences the net climate effect, while emissions from establishing and maintaining the forest are relatively minor. This highlights the role of long-term forest dynamics compared to initial project-related emissions.

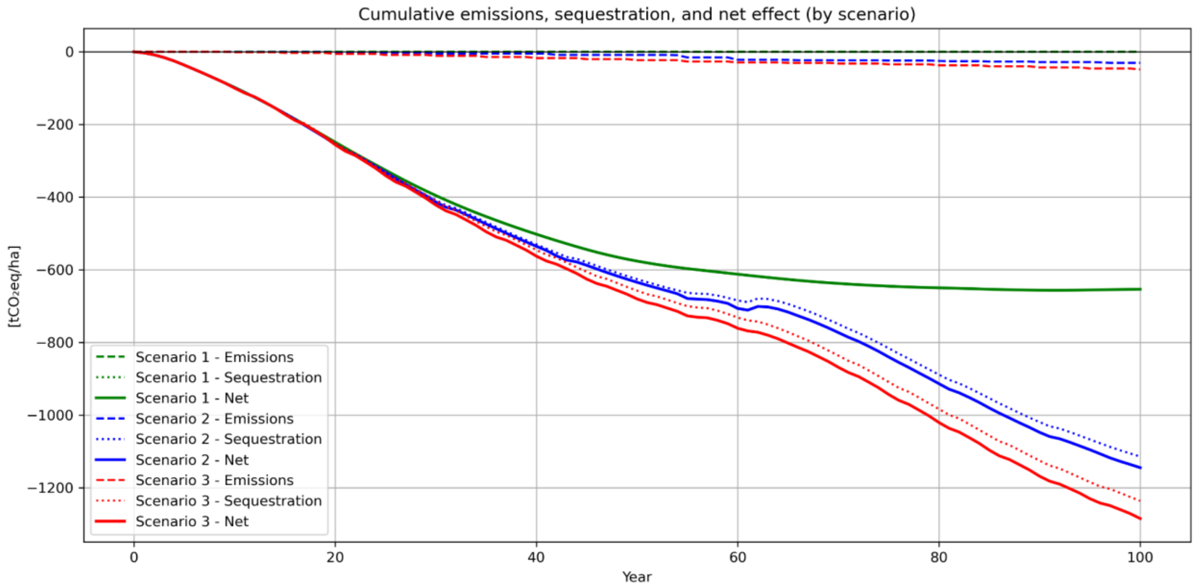

***Fig. 23** Cumulative emissions, sequestration, and net effect over 100 years for the three main scenarios.*

Regional potential

The regional potential for AR in Ireland over 100 years is as follows: scenario 1 could sequester 3.42 $GtCO_2$, scenario 2 5.99 $GtCO_2$, and scenario 3 6.72 $GtCO_2$ in total over 100 years.

If we take into account Ireland's national target of planting 490,000 hectares of forest by 2046, as outlined earlier, and apply the results of Scenario 2 over a 22-year period (assuming all trees are planted immediately), the estimated sequestration potential would reach approximately 0.14 $GtCO_2$-eq/ha by 2046.

Using the annual sequestration rate for Ireland (time horizon of 22 years) of -12.22 t CO_2-eq/ha/yr from the modelling, planting the full 490'000 ha target at once would result in an annual removal of about -5.99 Mt CO_2-eq. Based on 2024 emissions of 54 Mt CO_2-eq (excluding LULUCF), this would offset roughly 11 % of Ireland's current annual emissions. While this scenario assumes all planting occurs in the same year, it provides an upper-bound estimate of the short-term mitigation potential if the afforestation target were met immediately.

4.5 Sensitivity Analysis

The sensitivity analysis was conducted on a set of parameters defined in Section 3.8 (Table 4) of the methodology. Each parameter was individually modified by ±20% or, in the case of categorical variables, substituted with plausible or extreme alternatives. The goal of this analysis is to evaluate how changes in different input parameters affect the overall climate performance of AR projects.

While three distinct forest management regimes were examined in the core scenarios, the sensitivity analysis focuses exclusively on the medium management scenario (scenario 2). This means that all sensitivity scenarios are based on scenario 2 as the reference case, with only one parameter varied at a time. To assess the influence of these changes, both absolute values and relative changes are considered. The analysis includes:

- Total project emissions, carbon sequestration, and net balance over the entire time horizon (weighted by species shares) per hectare of forest

- Mean annual values for the same indicators, to control for the influence of time horizon, per hectare of forest

- Percentage changes compared to the standard scenario (scenario 2)

Results are presented in the form of bar charts that show the impacts in tonnes of CO_2-equivalent for one hectare of forest. Most parameters are changed only in the LCA part of the study and therefore do not affect sequestration; only time-related parameters or management regime do. Since sequestration has a much larger influence on the total net balance than the LCA component, the absolute values of the net balance are also reported there, as they show only minor differences.

4.5.1 Project emissions (LCA)

This section examines project emissions using LCA results across all analysed scenarios during the whole time horizon.

Figure 24 shows that scenario 1 is the only one showing positive emissions over at the end of the time horizon (0.20 tCO_2-eq), as it does not include any energy substitution. Most other scenarios show only minor variations around scenario 2, with close to -33 tCO_2-eq/ha emissions. This refers to scenarios with changes to road dimensions and density, seedling quantity and weight, and transport distances, which have little effect on total project emissions.

Some parameters, however, lead to more noticeable differences. The share of heat used in energy production, for example, significantly impacts the results. A reduced share of heat (and thus a greater share of electricity) leads to better outcomes (more sequestration), with an observed outcome of -40.11 tCO_2-eq/ha at the end of the time horizon.

Management styles also influence results. Aerial and terrestrial systems perform better than cable systems, as they show a sequestration of approximately -35 tCO_2-eq, compared to the -16.42 tCO_2-eq/ha of the later one. Scenario 3 performs well, with -48.57 tCO_2-eq, which is consistent with earlier findings showing reduced efficiency and biomass availability.

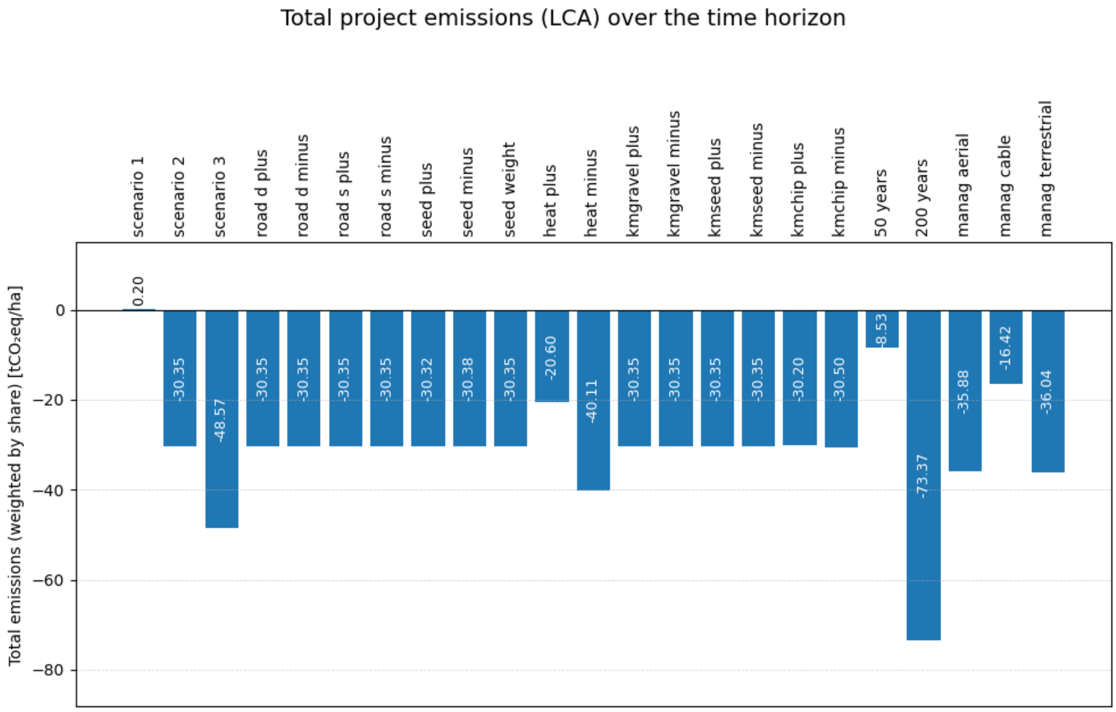

Fig. 24 Comparison of total project emissions (LCA) over 100 years for all scenarios in [tCO$_2$-eq/ha]

To assess the influence of time horizon, the second graph (Fig. 25) presents results on a mean annual basis for the 50- and 200-year scenarios. It shows that extending the time horizon increases sequestration, while a shorter horizon results in lower performance. This is likely because biomass has less time to grow or because the rotation period exceeds 50 years, preventing the substitution benefits that occur after the final harvest. Scenario 3 shows the highest removal rate over all other scenarios tested.

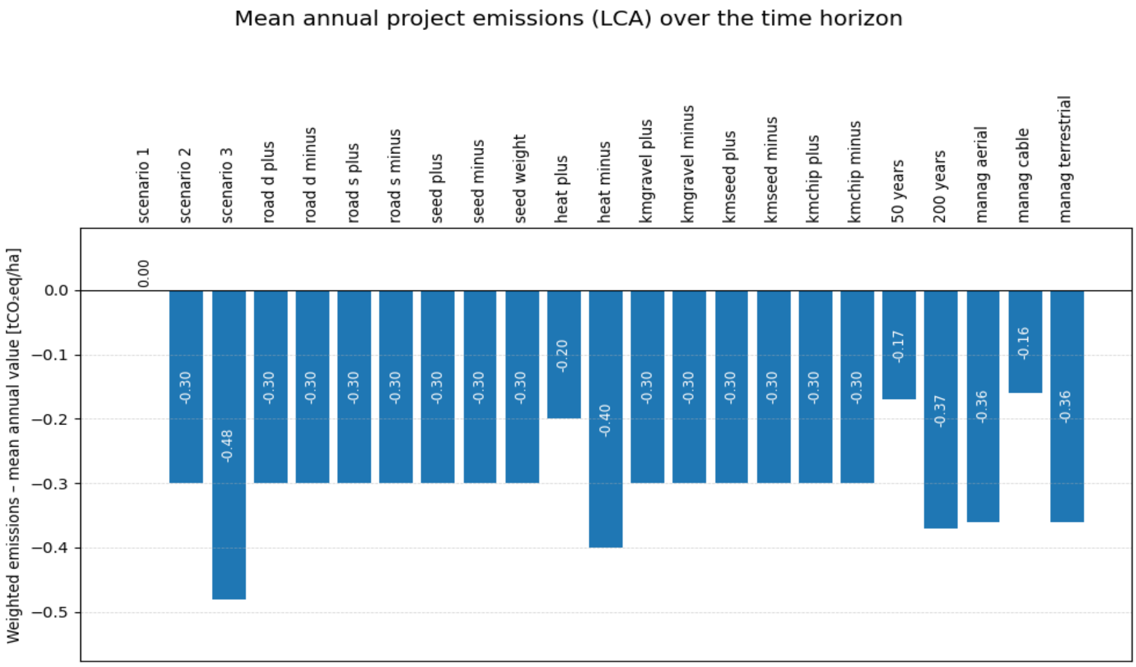

Fig. 25 Comparison mean annual project emissions (LCA) over 100 years for all scenarios in [t CO$_2$-eq/ha/year]

In summary, it seems that in addition to management regimes as seen before, the management style also has an impact on the outcome. And parameters that are closely related to the amount of biomass, like the time horizon, or the share of heat (based on the amount of wood), also have a significant impact.

4.5.2 Biomass sequestration (CO2FIX)

Now looking at the biomass sequestration under different parameters in Figure 26. Since most parameters are defined and used within the LCA model, very few of them influence the amount of biomass sequestered. As discussed earlier, the three main scenarios have different biomass outcomes, but the only other parameter that could influence it is the time horizon. This explains why most scenarios have a mean annual sequestration rate of -11.03 tCO_2-eq.

A shorter time horizon (50 years) results in a higher sequestration rate (-12.27 tCO_2-eq/ha/yr), while a longer time horizon shows a lower sequestration rate (-9.91 tCO_2-eq/ha/yr). This suggests that forest growth, and therefore carbon uptake, is more intense during the first decades of the project.

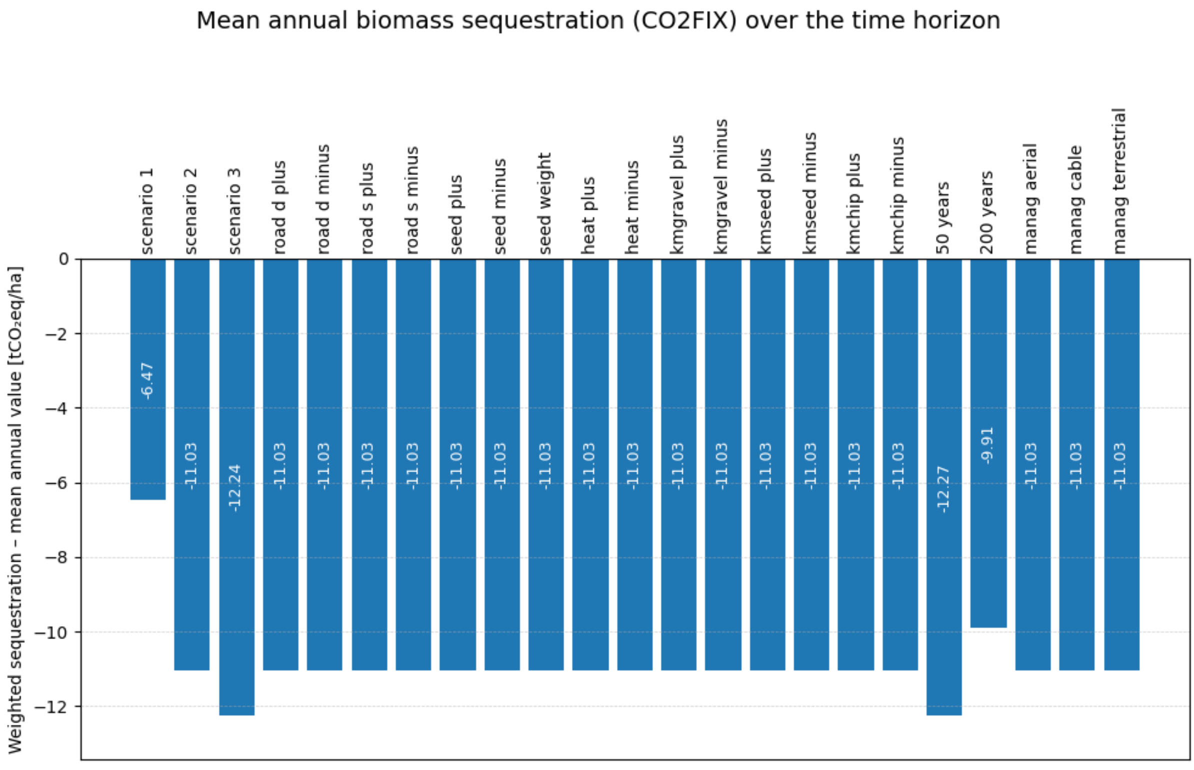

Fig. 26 *Comparison mean annual biomass sequestration (CO2FIX) over 100 years for all scenarios in [t CO_2-eq/ha/year]*

4.5.3 Net balance of emissions

Looking at the net balance, and given that project emissions are small compared to carbon sequestration from the CO2FIX model, little change is expected in the results compared to the previous section.

Figure 27 shows that most scenarios are very close to the reference scenario (scenario 2), which has a mean annual sequestration rate of -11.33 tCO_2-eq/ha/yr. Changing the heat parameter results in only ±0.10 tCO_2-eq/ha/yr difference, and the cable yarder management is also close at -11.20 tCO_2-eq/ha/yr. Scenario 3 performs best (-12.72 tCO_2-eq/ha/yr), followed by the 50-year scenario (-12.44 tCO_2-eq/ha/yr). The longer time horizon performs slightly less well (-10.28 tCO_2-eq/ha/yr), and the first scenario is far behind (-6.47 tCO_2-eq/ha/yr).

These results support that construction- and maintenance-related parameters have little impact on the overall carbon balance, while the management regime and time horizon have the greatest influence through their effect on biomass production and harvest.

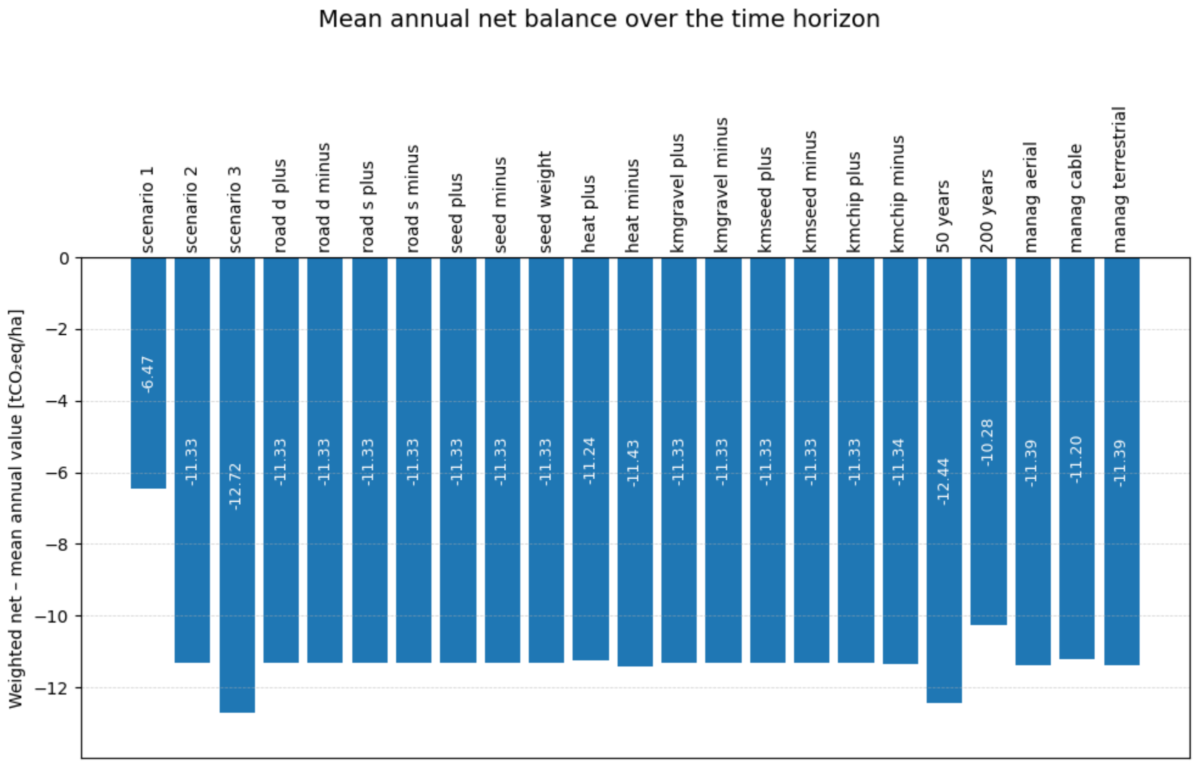

***Fig. 27** Comparison mean annual net balance over 100 years for all scenarios in [tCO_2-eq/ha/year]*

4.5.4 Relative impact of parameter changes

Table 10 shows how each parameter affects the results when increased or decreased by 20%, compared to the reference scenario (scenario 2). This helps identify which parameters have the biggest influence and where improvements could be made.

Overall, scenario 1 performs much worse across all categories, while scenario 3 performs better, especially in terms of LCA emissions. The heat share has a strong impact on the LCA results but a very small effect on the total net balance. Similarly, the different management styles affect the LCA part but have little influence on the overall climate outcome. Time horizon also plays an important role and should be considered when designing a project, and will be discussed in more detail in the following chapter. Most other parameters, such as those related to transport or infrastructure, have an insignificant effect (<0.01%), especially when looking at net carbon balance or annual sequestration rates.

These results reinforce the idea that parameters influencing forest growth dynamics, such as management intensity and time horizon, play a much larger role in determining climate performance than operational parameters like road building or seedling transport.

Table 10 *Percentage of change compared to scenario 2 in emissions, sequestration and net balance, for annual mean and total over the time horizon. Red colors indicate a negative change (more emissions, less sequestration, green colors indicate a positive change (less emissions, more sequestration).*

	Changes in annual project emissions [%]	Changes in annual biomass sequestration [%]	Changes in annual net balance [%]	Changes in total project emissions [%]	Changes in total biomass sequestration [%]	Changes in total net balance [%]
scenario 1	100.00	-41.34	-42.89	100.66	-41.35	-42.92
scenario 3	-60.00	10.97	12.27	-60.03	10.93	12.23
road d plus	0.00	0.00	0.00	0.00	0.00	0.00
road d minus	0.00	0.00	0.00	0.00	0.00	0.00
road s plus	0.00	0.00	0.00	0.00	0.00	0.00
road s minus	0.00	0.00	0.00	0.00	0.00	0.00
seed plus	0.00	0.00	0.00	0.10	0.00	0.00
seed minus	0.00	0.00	0.00	-0.10	0.00	0.00
seed weight	0.00	0.00	0.00	0.00	0.00	0.00
heat plus	33.33	0.00	-0.79	32.13	0.00	-0.85
heat minus	-33.33	0.00	0.88	-32.16	0.00	0.85
kmgravel plus	0.00	0.00	0.00	0.00	0.00	0.00
kmgravel minus	0.00	0.00	0.00	0.00	0.00	0.00
kmseed plus	0.00	0.00	0.00	0.00	0.00	0.00
kmseed minus	0.00	0.00	0.00	0.00	0.00	0.00
kmchip plus	0.00	0.00	0.00	0.49	0.00	-0.01
kmchip minus	0.00	0.00	0.09	-0.49	0.00	0.01
50 years	43.33	11.24	9.80	71.89	-43.84	-44.59
200 years	-23.33	-10.15	-9.27	-141.75	78.83	80.50
manag aerial	-20.00	0.00	0.53	-18.22	0.00	0.48
manag cable	46.67	0.00	-1.15	45.90	0.00	-1.22
manag terrestrial	-20.00	0.00	0.53	-18.75	0.00	0.50

5. Discussion

5.1 Introduction on the discussion

This chapter discusses the main findings of the study in relation to the overall research question: *How effective is afforestation and reforestation as a carbon dioxide removal strategy in Europe when evaluated using a life cycle approach.*

First, the potential for AR at the regional level was assessed using spatial data from Griscom et al. (2017), with a specific focus on Ireland as a case study. This is discussed in Section 5.1. Second, the amount of carbon that can be sequestered over time depending on tree species and forest management regimes was evaluated using the forest growth model CO2FIX. These results are discussed in Section 5.2. Third, the life cycle emissions associated with implementing and managing forest projects, both direct and avoided, were quantified using Brightway25 and are discussed in Section 5.3. Fourth, the net climate impact was assessed by comparing emissions and sequestration over time. This is presented in Section 5.4. Finally, a sensitivity analysis was conducted to identify which parameters have the strongest influence on the net balance. This helps determine which assumptions are most critical when applying the proposed framework. These insights are discussed in Section 5.5.

5.1 Regional settings

Meteorological data

In this study, meteorological data were averaged at the country level and then applied uniformly to each tree species. As a result, regional variations in climate within a country were not represented. For Ireland, where climatic variation is relatively limited, this simplification is unlikely to have a major influence on the results. However, in larger countries or in those with distinct climatic zones, such an approach could introduce greater uncertainty. In such cases, applying the model at the level of climatic regions rather than entire countries could provide a more accurate representation of temperature and rainfall.

In addition, the meteorological data were used as is and considered adequate, as they come from official sources. However, they are static, meaning that possible changes in temperature, rainfall, or other climate conditions over the 100-year period are not included. In reality, such changes could affect forest growth, mortality, and soil carbon. Adding climate projections could make the model more realistic, especially in the current context of climate change, but it would also make it much more complex and is beyond the scope of this study.

AR potential map

The map used for this study (Griscom et al., 2017) identified 5.2 million hectares of potentially eligible land for AR in Ireland. However, the accuracy of this estimate deserves further scrutiny. According to Farrelly and Gallagher (2015), only about 3.75 million hectares (or 54% of Ireland’s land area) are considered *“most likely to have potential for forestry expansion,”* once key constraints are taken into account. These include biophysical, biological, and policy-related limitations, which reduce the realistically available area for AR.

In addition, Fesenmyer et al. (2025) provide an important critique of global reforestation potential estimates. They emphasize that existing global AR maps are highly variable and have been widely criticized for being overly optimistic, which limits their reliability for policymaking and climate planning. Their analysis showed that, once more conservative forest definitions and exclusion criteria were applied, the estimated AR potential was 71–92% smaller than previous assessments. Despite this, AR remains the largest and most cost-effective natural climate solution, but the study urges for more conservative approaches when developing spatial estimates. Notably, the map used in this thesis is among those referenced in their analysis, highlighting the need to interpret results carefully and contextually.

Potential for improvement

These findings suggest that while Ireland appears to have substantial potential for AR, the actual area available may be considerably smaller when more conservative or detailed criteria are applied. This analysis could be further improved by incorporating future climate scenarios, which would provide a more nuanced understanding of how climate change might influence forest growth and land availability.

5.2 Forest growth model results (CO2FIX)

5.2.1 Summary of results

Scenario 1 (no management): In all three species, this scenario leads to the highest total carbon storage over time. Biomass accumulates rapidly and plateaus as forests mature, with no major disruptions. Soil carbon increases steadily as more organic material is left untouched. This scenario maximizes long-term carbon sequestration but includes no harvesting interventions.

Scenario 2 (moderate management): Biomass fluctuates due to thinning events and final harvests, but forests still regrow in between, allowing for moderate overall carbon storage. Soil carbon shows visible spikes after harvesting, especially final felling, with some upward trends over time. This scenario balances carbon accumulation with moderate forest use.

Scenario 3 (heavy management): Frequent thinning keeps biomass consistently lower, and soil carbon increases more slowly with smaller fluctuations. Carbon sequestration is the lowest across all species, though it remains relatively stable within cycles. This scenario limits forest carbon storage significantly due to repeated biomass extraction.

5.2.2 Comparison with existing literature

Bernal et al. (2018) report, for a temperate humid climate comparable to Ireland, sequestration rates of -9.5 t CO_2-eq/ha/year for oak, -11.8 t CO_2-eq/ha/year for broadleaf species (comparable to black alder), and -11.6 t CO_2-eq/ha/year for coniferous species, over the first

20 years after planting. According to Table 7, the sequestration rates for the first 20-year period are of a similar magnitude for black alder in all scenarios, approximately half as high for common oak, and roughly twice as high for Norway spruce.

When considering all species together, weighted by the shares defined in the parameter settings, the average sequestration rate across scenarios is approximately -13 t CO_2-eq/ha/year. This aligns closely with the value reported by COFORD (1999), which found an average carbon storage rate of 12.32 t CO_2-eq/ha/year for Irish forests. And is closer to amounts presented by Bernal et al. (2018).

This suggests that, while species-specific deviations are discussed later, the model appears to provide an adequate representation of forest growth overall. When all species are combined, their differing growth patterns likely smooth each other out, resulting in aggregated sequestration rates that align well with values reported in the literature.

5.2.3 Discussion on the forest growth model

Building species model with mixed data source

As all species were not modelled in the same way, results were presented by species rather than by scenario. Presenting results by scenario could lead to misleading interpretations, for instance, it might suggest differences driven by forest management, when in fact they could be due to the way each species was constructed in the model.

It was observed clearly in the results that Norway spruce outperforms the two other species in terms of sequestration. However, the aim was not to evaluate which species is "better," but rather to explore how different management scenarios influence outcomes for each species individually.

The three species used in the model were built with different datasets:

- Common oak and Norway spruce both used yield tables from the EFISCEN database.

- Back alder, however, had no adequate EFISCEN data and was instead built using regional literature.

- For biomass allocation (foliage, roots, branches), Norway spruce relied on the original CO2FIX data, while the other two species used literature values for broadleaf trees.

- All species used the same soil module, which was based on the same meteorological data, though growing seasons varied slightly.

This raises the question of whether Norway spruce's apparent outperformance is the result of biological differences or an artefact of the model's construction.

According to Bernal et al. (2018), in temperate humid climates, coniferous and broadleaf species show similar sequestration rates in the first 20 years. This would imply that the strong differences in model outputs are not due to the species type. In Scenario 1, Norway spruce gives reasonable results that align well with Bernal et al. (2018) (Table 7), yet still shows sequestration rates twice as high as the other species, again suggesting the difference is not due to the scenario either.

One possibility would be that the growing season duration chosen for Norway spruce is overestimated.

Overall, compared to Bernal et al. (2018), the model does not seem to capture sequestration values with high accuracy. However, Black et al. (2009) and COFORD (2022) provide region-specific sequestration rates for Ireland that are closer to the model's results. While Bernal et al. (2018) gives general estimates by climate zone, these other studies are more relevant to the actual conditions in this project.

Also, when all species are grouped together according to their shares, the average sequestration rate for the whole forest is close to the value given by COFORD (1999) for Irish forests. This gives confidence in the overall validity of the model, despite limitations in species-level accuracy.

Modelisation of thinning

The timing and amount of thinning were based on information from the literature, but since most sources focus on specific cases, regions, or species, it is difficult to find general values. As a result, the choices made here are not entirely arbitrary, but some assumptions were necessary. This aspect was not tested further, as varying thinning years or amounts for three different species would be complex. Instead, three management scenarios that appear plausible were developed, which could be adapted for specific projects if needed.

Mortality rates

We set the tree mortality rate to 1% in Scenario 1 in order to simulate a forest that does not grow indefinitely without limits. This decision is supported by Laarmann et al. (2009), who found an average annual mortality rate of 1.3% in Estonian forests, a value close enough to validate our assumption for the unmanaged scenario.

In contrast, mortality was not included in Scenarios 2 and 3, since thinning and harvesting operations already remove a portion of the standing biomass. It was assumed that trees that would naturally die each year would, in managed scenarios, be effectively removed through those interventions. In that sense, natural mortality is implicitly accounted for in the harvested biomass, and its explicit inclusion was expected to have an insignificant effect on overall results.

This assumption was not tested directly, although it could have a minor influence, especially considering that biomass accumulation strongly affects the net carbon balance.

Other assumptions

Several key parameters in the model were taken directly from scientific literature and used without further modification, as they are well established and widely applied in forest carbon studies. These include yield tables, carbon content, wood density, turnover rates, and rotation lengths. While yield tables and rotation lengths can vary considerably depending on species, management practices, and regional conditions, the selected values were chosen to reflect realistic growth patterns and are supported by credible sources. The carbon content of biomass was fixed at 50 % by dry weight, following the widely accepted value reported by Schelhaas et al. (2006), which is considered robust for the purposes of this analysis. Wood density and turnover rates were also derived from peer-reviewed studies. Given the reliability of these data and their common use in similar research, no further sensitivity testing was undertaken for these parameters.

Conclusion on model reliability

Some potentially influential factors were excluded from the CO2FIX model to keep the scope manageable. These include natural mortality in managed scenarios, interspecies competition, and natural disturbances such as fires, pests, or storms. Those processes are actually a key limitation of AR as a CDR strategy is the risk of releasing stored CO_2 back into the atmosphere when such disturbances occur. This means that permanence cannot be guaranteed, although it can be improved through appropriate management and protection measures. While these processes are relevant, their exclusion simplifies the modelling and avoids adding uncertain parameters without sufficient data support.

Certain fixed parameters in CO2FIX, such as allocation ratios and turnover rates, were taken directly from literature sources and not varied further. The rotation period for each species may be particularly important, as it determines the timing of final felling and thus affects sequestration and emissions patterns, especially when viewed under different time horizons.

Future work could explore the sensitivity of results to rotation lengths, disturbance events, and incorporating region-specific mortality rates for managed forests. This would allow for a more detailed representation of long-term carbon dynamics under varying environmental and management conditions.

It can therefore be concluded that, although the tree models built using CO2FIX and various data sources may not perform with perfect accuracy, they appear sufficiently reliable for the purposes of this study.

5.3 LCA results (Brightway25)

5.3.1 Summary of results

The LCA model evaluates emissions associated with forest project activities, including site preparation, planting, forest management, and transport, as well as negative emissions from energy substitution. The results show clear differences across the three main scenarios:

- **Scenario 1 (no management):**
  Very low emissions (~200 kgCO_2-eq/ha) limited to planting and road construction. No energy substitution occurs, resulting in no negative emissions. The overall climate impact of this scenario depends almost entirely on carbon sequestration from forest growth.

- **Scenario 2 (moderate management):**
  Project-related emissions increase due to regular thinning operations, material transport, and final harvesting (~15'500 kgCO_2-eq/ha). However, energy substitution from harvested biomass offsets a significantly larger amount of emissions, resulting in net negative LCA emissions of approximately -30'350 kg CO_2-eq/ha.

- **Scenario 3 (intensive management):**
  More frequent interventions lead to higher overall emissions (~24'500 kgCO_2-eq/ha), but they also generate larger substitution benefits, resulting in the most favorable net LCA outcome among all scenarios, with total net emissions of approximately -48'570 kgCO_2-eq/ha.

Across all scenarios, project-related emissions remain small compared to the sequestration potential estimated through the biomass model. The LCA emissions represent less than 2% of total carbon removals in all three scenarios. Forest management practices that generate more harvested biomass (and therefore more substitution potential) lead to more favorable LCA outcomes despite the additional emissions generated.

5.3.2 Comparison with existing literature

Brunori et al. (2017) report emissions of 5 753 kg CO_2-eq/ha from management processes over a 34-year period, representing around 1% of the total climate impact. Their scope includes planting, site preparation, thinning, and harvesting, with management emissions quickly offset by sequestration. In the present analysis, the share of emissions is roughly double; however, it includes emissions from post-harvest energy production, an activity with high associated impacts, and uses a time horizon almost three times longer. For the standard scenario, positive emissions (from planting, site preparation, harvesting, and energy production, excluding avoided emissions) are around 15 500 kg CO_2-eq/ha, approximately three times higher than Brunori et al. (2017)'s results. Given these differences in scope and time horizon, the absolute values appear to be of a similar order of magnitude.

Lefebvre et al. (2021) report first-year project emissions of 1.27 t CO_2-eq/ha, considerably higher than the 0.20 t CO_2-eq/ha calculated here (in the standard scenario). Their case study differs substantially in context: it is located in another region, the forest is left untouched within a reserve, and biochar is applied to enhance sequestration. Moreover, the project involves three cleaning operations in the first year, which likely accounts for the significantly higher establishment-related emissions compared to the present results.

These comparisons focus solely on the emissions side of the analysis. The broader climate impact, including carbon sequestration and the net balance of the projects, is examined in the following section (Section 5.4).

5.3.3 Discussion on the life cycle-based model

Choice of a time horizon

The choice of time horizon acts less as a technical driver of emissions or sequestration and more as a definition of the reference point for the analysis. Extending or shortening the study period does not change the actual processes occurring in the forest, but it determines how much of these processes are included in the results. This is an important consideration when comparing studies, as differences in time horizon can influence the apparent performance of a project. For example, a short time horizon for a forest project may give the impression of higher efficiency if trees sequester more carbon in their early years, or if significant activities (such as a final harvest) occur after the end of the time horizon, as was the case for one species in this study. By contrast, a longer timeframe would capture slower growth phases and potential disturbances, leading to a lower annualised rate. Such effects are more relevant to how results are presented than to any measurable physical impact, which is why the use of mean annual values are interesting for comparison.

Heat of share in the substituted energy mix

In the model, the share of heat in the substituted energy mix is based on Ireland’s 2022 energy demand, with heat representing approximately 62% and electricity 38% (SEAI, 2023). The share of fossil energy in Ireland’s primary energy supply that year was 85.6%, and this value is used to scale the substitution effect, under the assumption that only fossil-based energy can be offset.

Interestingly, increasing the heat share in the substitution mix leads to a slight decrease in net carbon sequestration. While one might expect that substituting more heat, and therefore avoiding more fossil-based energy, would improve the net balance, this is not the case in the model. This outcome can be explained partly by the parameters of the substitution activity: energy is produced through a co-generation activity, where the modelled efficiency is 0.5 for heat and only 0.1 for electricity. Producing useful electricity requires more biomass input than producing heat, due to its lower conversion efficiency. Therefore, when the electricity share in the substituted energy mix is high, more wood is needed, which increases direct emissions from biomass combustion. If we instead increase the heat share, the total biomass requirement decreases, which reduces project emissions. However, this also means we substitute less fossil electricity. As a result, even though we burn less biomass, we also avoid fewer fossil emissions. This explains why increasing the share of heat leads to slightly lower emissions but also smaller substitution benefits, resulting in a less favorable net climate balance.

The overall effect of varying the heat share remains limited, with a maximum variation of only 0.12 t CO_2-eq/ha from the baseline scenario. Still, this highlights an important modelling consideration: although biomass is assumed to offset fossil emissions, it still releases CO_2 when burned, CO_2 that was previously sequestered during forest growth. Substitution only leads to a net benefit as long as the baseline assumes continued reliance on fossil fuels. In future decarbonized energy systems, this assumption may no longer hold, reducing or eliminating the benefit of substitution.

This shows a broader limitation of substitution-based approaches: avoided emissions are highly dependent on the baseline. While Ireland's current energy mix supports a strong substitution credit, long-term benefits would need to account for evolving energy systems. Incorporating such dynamics was beyond the scope of this study but represents an important direction for future research on biogenic CO_2 and the role of forest biomass in energy systems.

Seedling quantity and weight

The number of seedlings has a potential influence on total emissions In Scenario 1, where no forest management occurs after planting. This is because planting- and nursery-related emissions make up a significant share of the total in the absence of later operations. One of the species having two times more seedlings thus increase its overall footprint. In contrast, in Scenarios 2 and 3, where thinning and harvesting lead to much higher emissions, the impact of planting seedlings becomes negligible.

The number of seedlings varies widely in the literature. Fixed values wer selected based on available sources and tested through sensitivity analysis. Varying this number by ±20% had an insignificant effect on total emissions, and it did not appear to affect the final net balance. This is because the seedling number only influences nursery and transport emissions in the LCA, and has no link to the forest growth model.

However, if seedling numbers were also adjusted in the CO2FIX model, which influences biomass accumulation, a stronger effect might be observed for all scenarios.

As for seedling weight, multiplying it by 100 changed the overall results by less than 0.1% (Table 10), supporting the assumption to use a fixed value across species.

Road construction

Changes to road dimensions and density have only a negligible effect on total project emissions. According to Dolan et al. (2024), gravel road construction typically occurs several years after planting (around year 8). For simplification purposes, the road was assumed to be built at the time of planting in this study, as this timing is not expected to significantly influence the results. The road construction process was also simplified, omitting the multiple layers typically found in a standard road. It was further assumed that the road would last for the entire time horizon, whereas Dolan et al. (2024) note that such roads require periodic maintenance and additional gravel every few years. Given the minimal influence of the road component on the results, its construction is unlikely to have a notable impact. Including maintenance could slightly increase the footprint due to additional gravel extraction and transport, but this effect is expected to remain very small.

Transport modelling

Transport distances have little effect on overall emissions. It was modelled exclusively as being performed by unspecified lorry, in order to simplify the model and avoid introducing additional modes such as rail. This approach is likely appropriate in the case of Ireland, where distances are relatively short and lorry transport is dominant for the transport of biomass (Dolan et al., 2024). However, in larger countries or in cases where a significant share of transport would be by rail or ship, the choice of mode could have a greater influence on the results.

Management style allocation

The sensitivity analysis shows that scenarios with 100 % aerial or 100 % terrestrial harvesting perform better than those with 100 % cable yarder use. This suggests that the cable yarder either has much higher emissions or that its scaling in the model does not fully reflect real-world conditions. This aligns with the LCA results, where even with only 29 % of the operations performed by cable yarder (and 71 % terrestrial), the cable yarder still produced roughly ten times more emissions than the skidder used in terrestrial management. Activity scaling was based on literature values, but these may come from different models or contexts that are not perfectly comparable. The chosen values are assumed to be sufficiently representative, and the allocation of management methods is considered reasonable. Since regional practices can vary, the approach can easily be adapted for location-specific conditions.

Static emissions factors

This study does not account for potential changes in emission factors over time. The analysis was performed using a standard database without built-in scenarios for the evolution of background emissions. Including such dynamics could provide a more realistic representation, particularly for long-term projects where decarbonisation of the energy mix or machinery improvements may occur. Exploring this aspect could therefore be an interesting direction for future research.

Conclusion on model reliability

Overall, the assumptions used in the forest model aim to stay realistic while keeping things manageable, using literature and regional data whenever possible. Some parameters, like road construction details or transport distances, barely change the results, while others, such as management style or the heat share in the energy mix, can have a bigger influence on the net climate balance. The model does not include changes over time in things like emission factors, climate, or forestry practices, which could affect long-term outcomes. Future work could add these dynamics, try different management strategies, and connect seedling parameters in the LCA to the forest growth model, so that planting choices directly influence biomass growth. These improvements would make the model more robust and adaptable to other regions or future scenarios.

5.3 Net balance results

5.4.1 Summary of results

The net climate impact of each scenario was calculated by combining carbon sequestration from the CO2FIX model with project emissions from the LCA.

Scenario 1 (no management) showed the only positive net balance due to uninterrupted biomass growth but no energy substitution benefits. (0.2 tCO_2-eq/ha)

Scenario 2 (moderate management) shows a better outcome with some emissions from thinning and harvesting but also allowed fossil fuel substitution. This resulted in a balanced outcome, combining storage and avoided emissions. (-30.35 tCO_2-eq/ha)

Scenario 3 (intensive management) generated the best net balance score due to frequent operations, but also delivering substitution benefits. (-48.57 tCO_2-eq/ha)

Looking at the graphical results (Fig. 23), the mixed-species approach used here smooths the temporal variations in sequestration and emissions. Since the three selected species have different rotation periods, peaks from harvesting or thinning in one species are partly offset by steady sequestration in the others, resulting in less pronounced fluctuations in the combined scenario curves. This effect may also explain why thinning operations are less visible in the net balance graph when all species are aggregated.

Overall, the results suggest that forest growth dynamics (biomass accumulation and harvest intensity) have a greater influence on climate outcomes than project-related emissions.

5.4.2 Comparison with existing literature

When comparing the net balance results with existing literature, several points emerge. Sonne et al. (2006) assume that emissions from forestry operations are minimal and therefore focus solely on forest biomass carbon. The results of this study support this assumption, as positive emissions from forestry activities account for less than 2 % of the total climate effect of a forest project. This also implies that avoided emissions from energy substitution are not considered in their approach, and even though these remain relatively small, they still have a greater influence than direct project emissions.

Terlouw et al. (2021) report -0.8 to -1 tCO_2-eq/ha/year sequestered for a similar project, which is considerably lower than the -6 to -2 tCO_2-eq/ha/year found in this analysis. A likely explanation is that their assessment does not account for energy substitution benefits, although even without substitution the biomass sequestration rates obtained here would remain substantially higher. Further differences may arise from the forest types, climatic conditions, or management regimes considered in their study.

Cooper et al. (2022) estimate that sequestering 1 tCO_2-eq results in 36 kgCO_2-eq of associated emissions, representing 3.6 % of total sequestration. This is in line with, or slightly higher than, the values calculated in this analysis, where the ratio remains below 2 %. Their reported sequestration rate is -7 tCO_2-eq/ha/year, almost half of the value obtained for the standard scenario of this study. As with Terlouw et al. (2021), the absence of energy substitution in their assessment likely accounts for part of this difference.

Lefebvre et al. (2021) find that an AR project sequesters -0.51 tCO_2-eq/ha in the first year, compared to -3 tCO_2-eq/ha in the standard scenario of this study (scenario 2). They report first-year project emissions of 1.27 tCO_2-eq/ha, far higher than the 0.20 tCO_2-eq/ha calculated here. The difference might be explained by their case study context: the project is located in a different region, the forest is left untouched in a reserve, and biochar is applied to enhance sequestration. Moreover, the project involves three cleaning operations in the first year alone, substantially increasing establishment-related emissions.

5.4.2 Case study results: Ireland

Even under more conservative assumptions regarding the area available for AR, Ireland retains strong potential as a meaningful CDR strategy. Using the 3.75 Mha identified by Farrelly and Gallagher (2015) as most likely suitable for forestry expansion, this would correspond to a technical potential of -2.45 Gt CO_2-eq for scenario 1, -4.29 Gt CO_2-eq for scenario 2, and -4.82 Gt CO_2-eq for scenario 3 over a 100-year period.

Farrelly and Gallagher (2015) also introduce the objective of increasing the total forest area to 18% of the territory by 2046. This would require the plantation of 490 000 ha, which, at a sequestration rate of -12.22 t CO_2-eq/ha/yr, would deliver approximately -0.14 Gt CO_2-eq by 2046. This figure assumes all planting occurs at once, which is not realistic in practice, as planting would likely be staggered over time. The spatial distribution and timing of planting would therefore reduce the short-term potential.

This study can be replicated for different countries to enable comparison of their AR potential.

5.4 Conclusion on the overall model performances

Overall, the modelling framework developed in this study appears sufficiently robust to meet its purpose, even though it relies on simplifications and assumptions. Both the forest growth (CO_2FIX) and life cycle (Brightway2) models produced results that are consistent with values reported in the literature when aggregated across species and scenarios. While species-level outputs sometimes diverge from external data, these differences can often be explained by the way the species models were built or by variations in literature sources.

The LCA side of the framework shows that project-related emissions are generally very small compared to the amount of carbon sequestered. This confirms that the main drivers of climate performance are factors linked to forest growth dynamics. Sensitivity analyses indicate that some parameters, such as management style allocation or the share of heat in the substituted energy mix, can more or less noticeably affect the net climate balance, whereas others, like road construction details or seedling weight, have almost no influence.

The model’s main limitations stem from its static background data, exclusion of disturbance events, and simplifications in some processes. Nonetheless, the results provide a credible and transparent estimate of the net climate impact of AR projects under different management strategies and could be adapted for other regions with relative ease.

6. Conclusion

6.1 Summary of key findings

This study aims to answer the question: *How effective is afforestation and reforestation (AR) as a carbon dioxide removal strategy in Europe when evaluated using a life cycle approach?* To address this, spatial data were used to assess the regional AR potential, forest growth was modelled with the CO2FIX model, and life cycle emissions were calculated using Brightway25 with a dynamic approach. Ireland was used as the main case study. Both carbon sequestration and project-related emissions were considered, along with avoided emissions from energy substitution.

Using a conservative estimate of 3.75 Mha of land identified by Farrelly and Gallagher (2015) as most likely suitable for forestry expansion, Ireland's technical AR potential ranges from -2.45 Gt CO_2-eq in the no-management scenario (scenario 1) to -4.82 Gt CO_2-eq in the intensive-management scenario (scenario 3) over a 100-year period. At the European scale, applying the same assumptions gives a potential of -121 Gt CO_2-eq for the standard scenario (scenario 2). These findings confirm that AR can deliver significant carbon removal if implemented at large scale.

6.2 Main drivers of climate performance

Forest growth dynamics are the main driver of the net climate impact, whereas project-related emissions from establishment, maintenance, and harvesting account for less than 2% of the total impact. This means that processes linked to biomass growth have a far greater influence on the overall balance. The first key factor is the management regime, which determines how much wood is harvested and how often. In this study, no management scenario (scenario 1) reduced annual sequestrations by 42% compared to the standard scenario (scenario 2), while intensive management (scenario 3) increased it by 12%. The second factor is the management style, which influences results through differences in biomass output (ranging from a 1% decrease to a 0.5% increase in annual sequestrations). Finally, because biomass production also determines the potential for energy substitution, the share of heat and electricity in energy demand affects very slightly the net climate balance (± ~0.8% of change in the annual sequestration).

AR could make a significant contribution to Europe's carbon dioxide removal goals, provided it is implemented on appropriate land, supported by adequate management, and aligned with broader land-use and climate policies. However, the analysis also highlights important uncertainties, particularly regarding future climate conditions, disturbance risks, and the changing role of biomass in decarbonising energy systems.

6.3 Future directions and research

Future work should integrate dynamic climate and energy scenarios, along with region-specific disturbance probabilities, to provide more realistic estimates of AR potential. Applying this approach systematically across European countries would allow for more precise comparisons and help identify priority regions for AR deployment.

In conclusion, AR offers strong sequestration potential in Europe, with relatively low direct emissions. Its effectiveness depends primarily on biological growth patterns, while substitution benefits provide an additional, but temporary, boost under current fossil-heavy conditions. Realising this potential will require careful land selection, sustained policy support, and adaptive management to secure both the quantity and permanence of carbon stored.

Appendix A. Activity system for the forest project

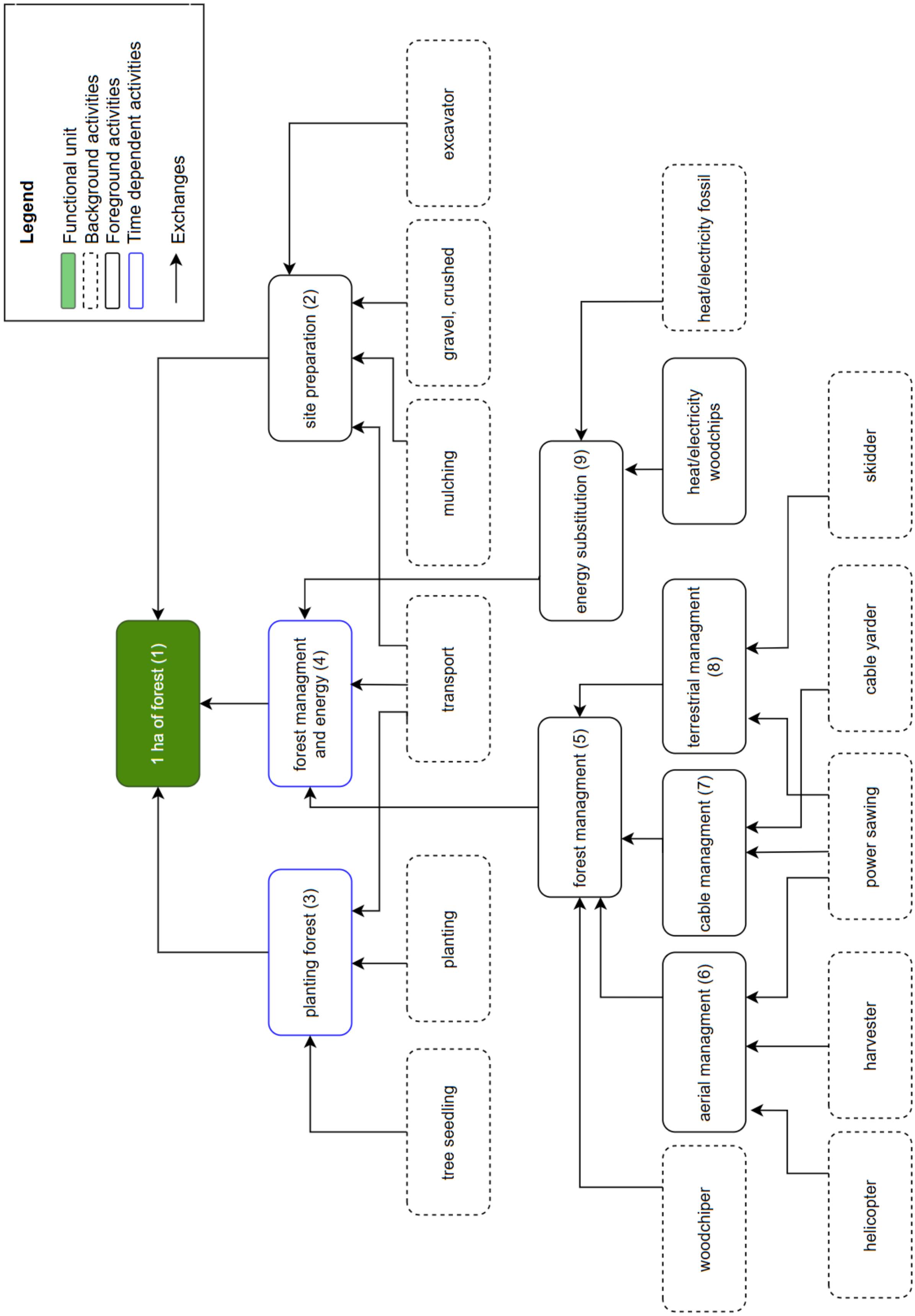

***Fig. A 1**: System model of the afforestation/reforestation LCA*

Appendix B. List of assumptions

***Table B 1**: System model of the afforestation/reforestation LCA*

Regional	Precipitation data is based on the year 2024 only (no multi-year average used).
	Selected tree species are assumed to represent the region adequately.
	Climate input data is taken from current sources and is not dynamically adjusted over time.
	Mountainous terrain is defined as elevations over 600 m (based on Swiss altitude classes).
	Country area data is approximate due to the map resolution used for spatial analysis.
Other	Forest project is not limited by socioeconomic constraints (e.g land ownership, funding, or policy).
	Trade-offs and co-benefits (e.g. biodiversity, water regulation) are not included in the calculations.
	Changing the number of seedlings affects emissions but not biomass accumulation.
LCA	The time horizon is fixed and does not account for long-term forest dynamics beyond that period.
	No emissions from previous land use or land use change are considered.
	Future efficiency improvements or emission factor changes are not accounted for.
	Transport distances for woodchips, seedlings, and gravel are fixed per scenario.
	Road size and density are defined based on local literature.
	The share of heat and electricity produced is based on regional energy profiles.
	Tree species shares are fixed from map-derived data.
	Number of seedlings is fixed from source data.
	Weight of seedlings is fixed across species
	Share of management types is calculated from terrain elevation and difficulty.
	Transport is modelled solely as unspecified lorry freight.
	A prospective LCA database (future energy mix) is not used.
	Assumes terrain with minimal vegetation, no toxic elements, no large rocks, and no major obstacles.
	Roads are built using gravel only, with substructure from local soil.
	Road durability is assumed sufficient for the entire time horizon.
	Swiss forestry activities are assumed valid and representative for all of Europe.
	Managing activities are scaled using literature-based productivity data.
	Management types are terrain-based (e.g. more aerial operations in mountainous areas).
CO2FIX	Carbon content of biomass is the same for all species.
	Wood density values are taken from literature sources.
	No interspecies competition is modelled.
	Turnover rates for foliage, branches, and roots are species-specific but fixed.
	CAI values are sourced from EFISCEN or literature and are assumed sufficiently accurate for modelling.
	Mortality is generally not included.
	Thinning years and thinning intensity are predefined and fixed.
	Rotation lengths are fixed per species.
	Biomass allocation parameters (foliage, roots, etc.) come from mixed literature sources.
	One species was modelled using CO2FIX data; the others were adapted from external sources.
	No CO_2 is sequestered in the first year (establishment year).
	No natural disturbances (e.g. fires, pests, storms) are included in the model.

Appendix C. LCA results per specie and scenario

Scenario 1 - Common oak

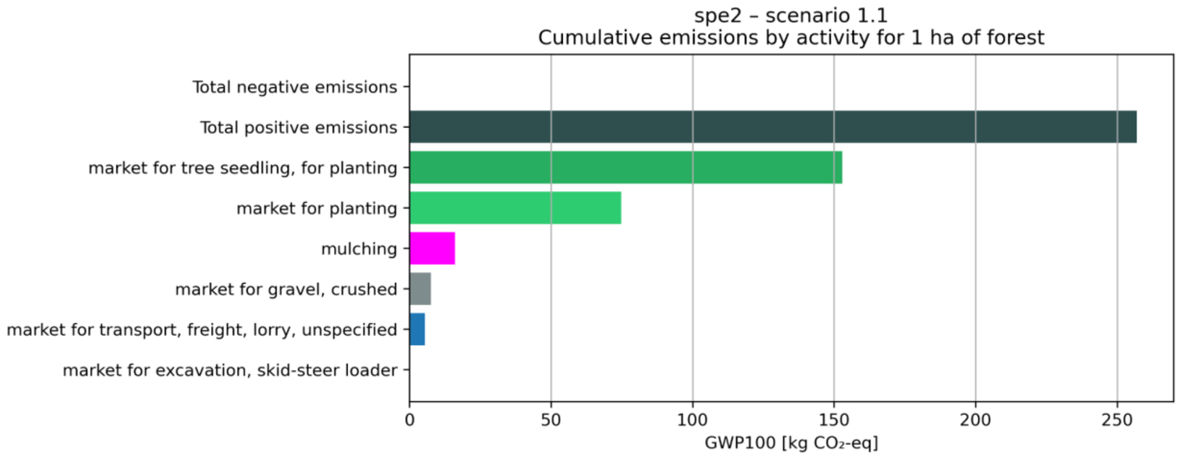

***Fig. C 1**: Cumulative emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 1, specie 2*

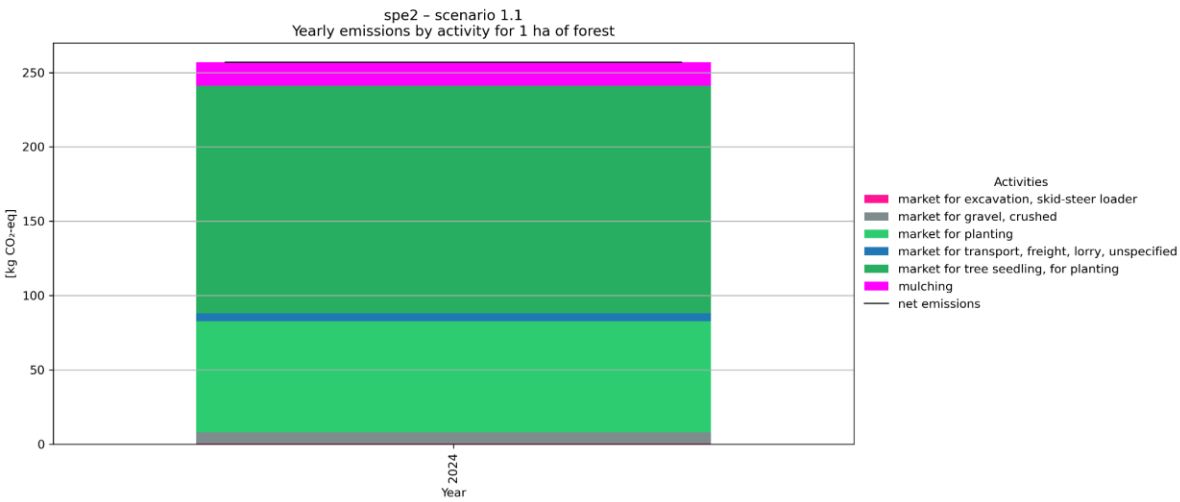

***Fig. C 2:** Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 1, specie 2*

Scenario 1 - Norway spruce

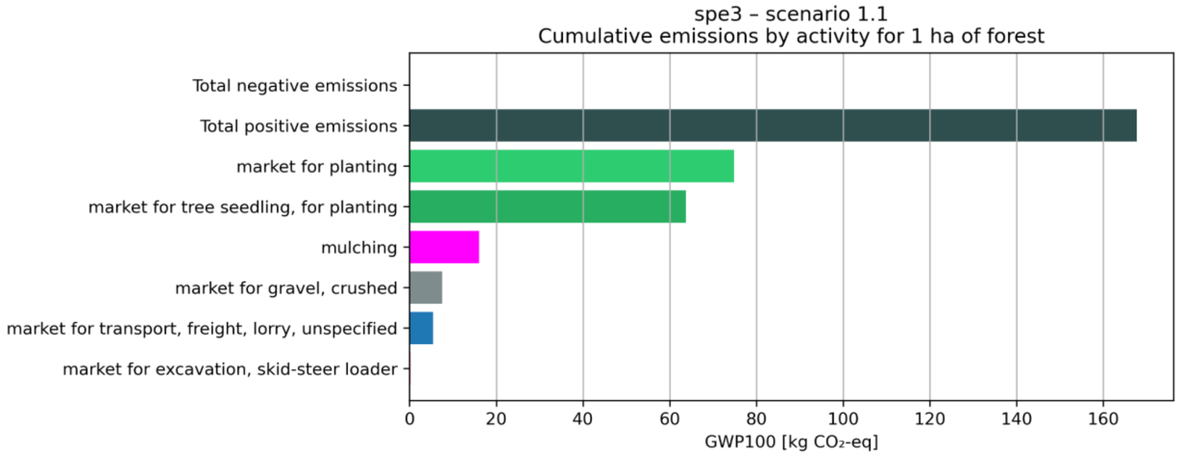

***Fig. C 3**: Cumulative emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 1, specie 3*

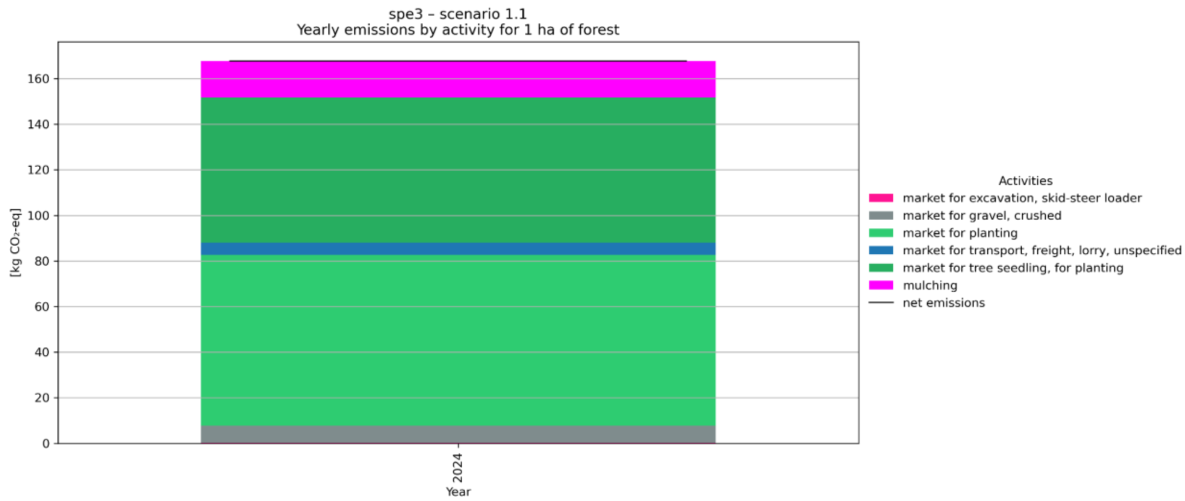

***Fig. C 4:** Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 1, specie 3*

Scenario 2 - Common oak

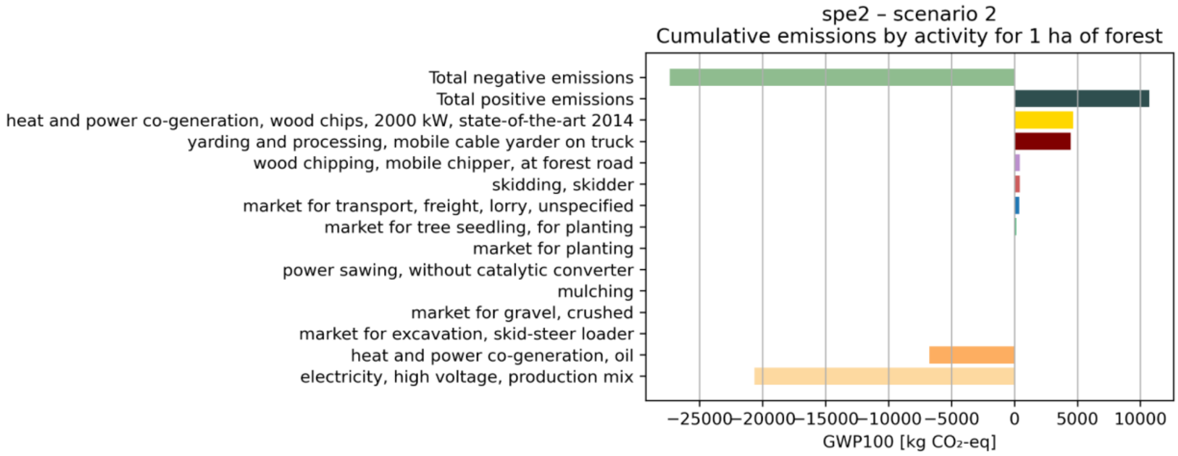

***Fig. C 5**: Cumulative emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 2, specie 2*

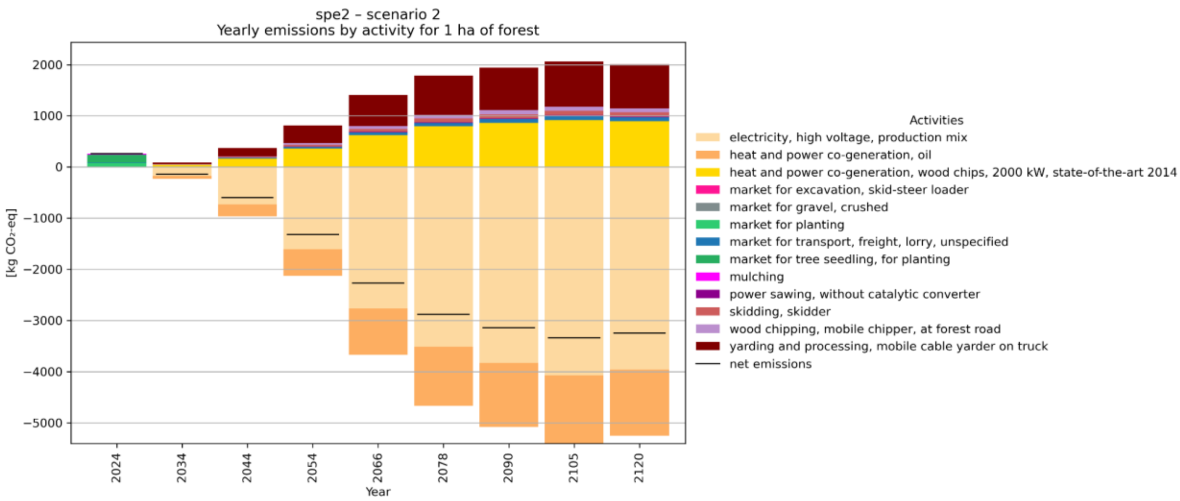

***Fig. C 6**: Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 2, specie 2*

Scenario 2 - Norway spruce

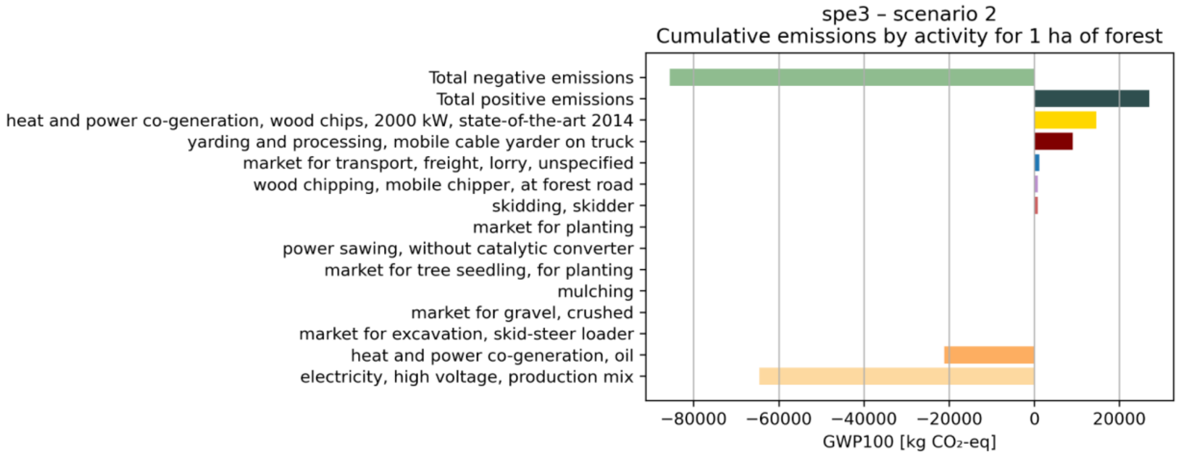

Fig. C 7: *Cumulative emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 2, specie 3*

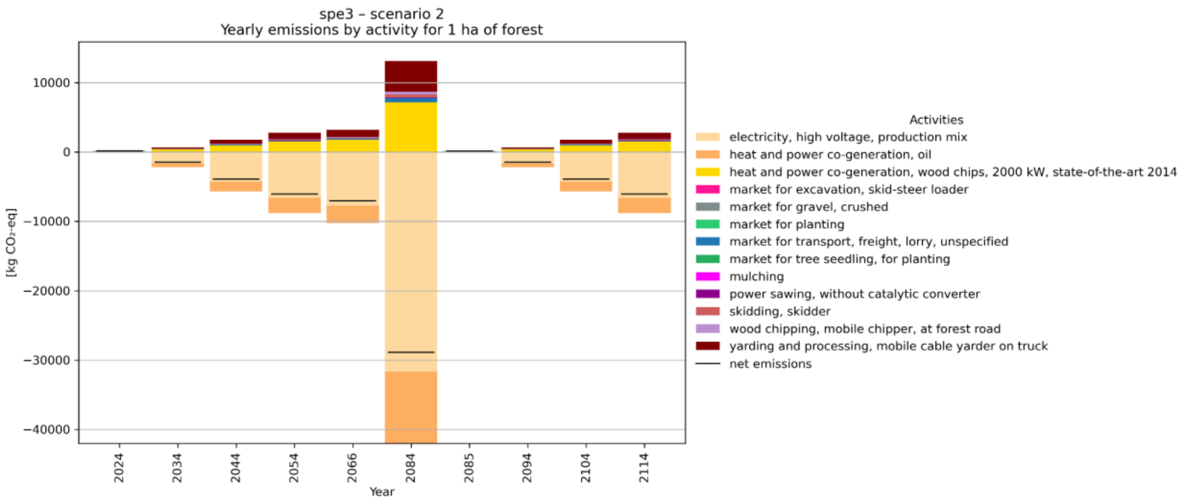

Fig. C 8: *Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 2, specie 3*

Scenario 3 - Common oak

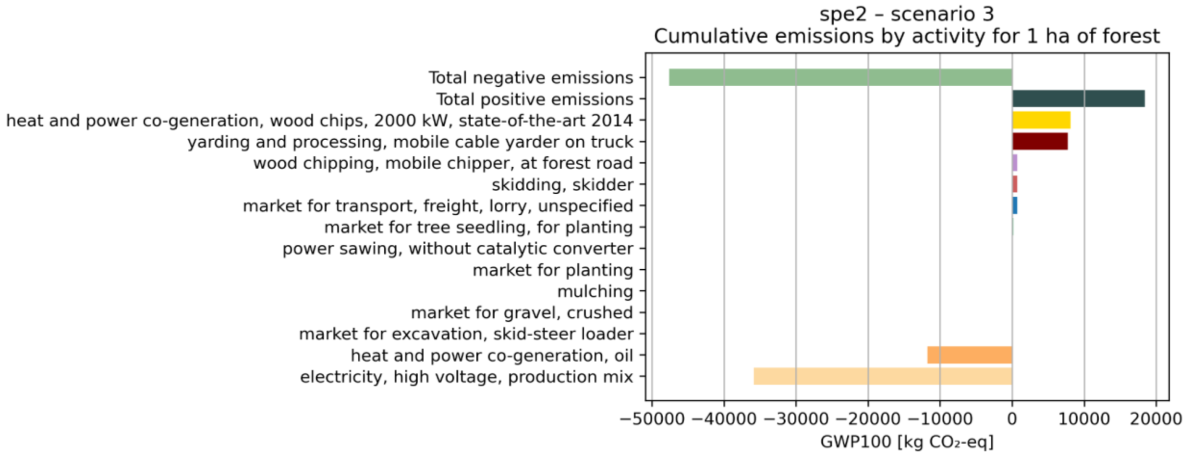

***Fig. C 9**: Cumulative emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 3, specie 2*

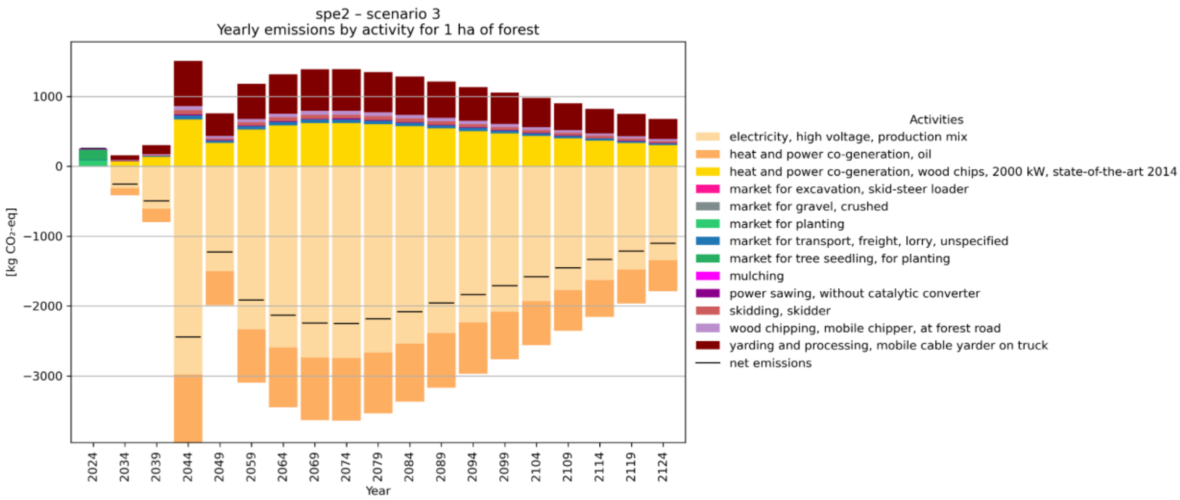

***Fig. C 10**: Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 3, specie 2*

Scenario 3 - Norway spruce

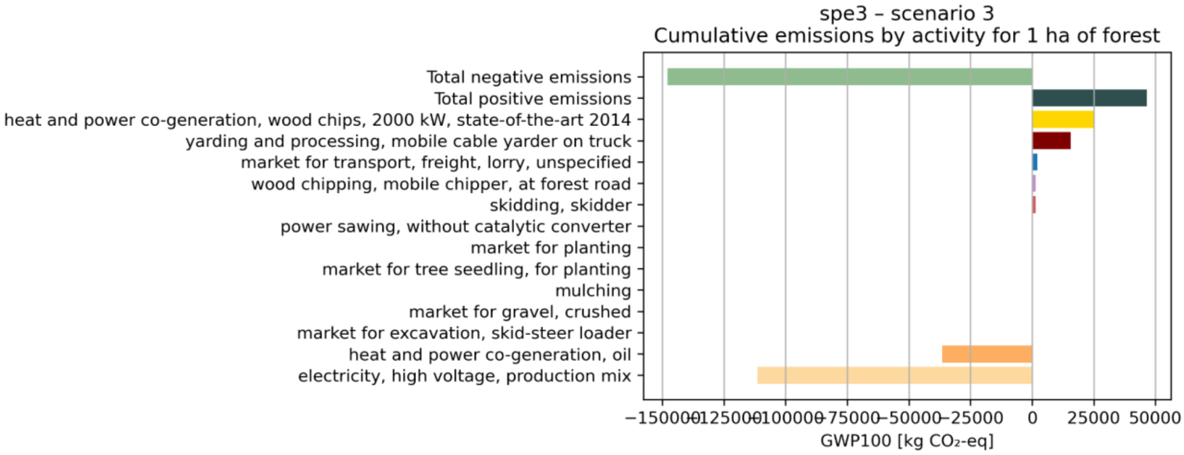

Fig. C 11: *Cumulative emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 3, specie 3*

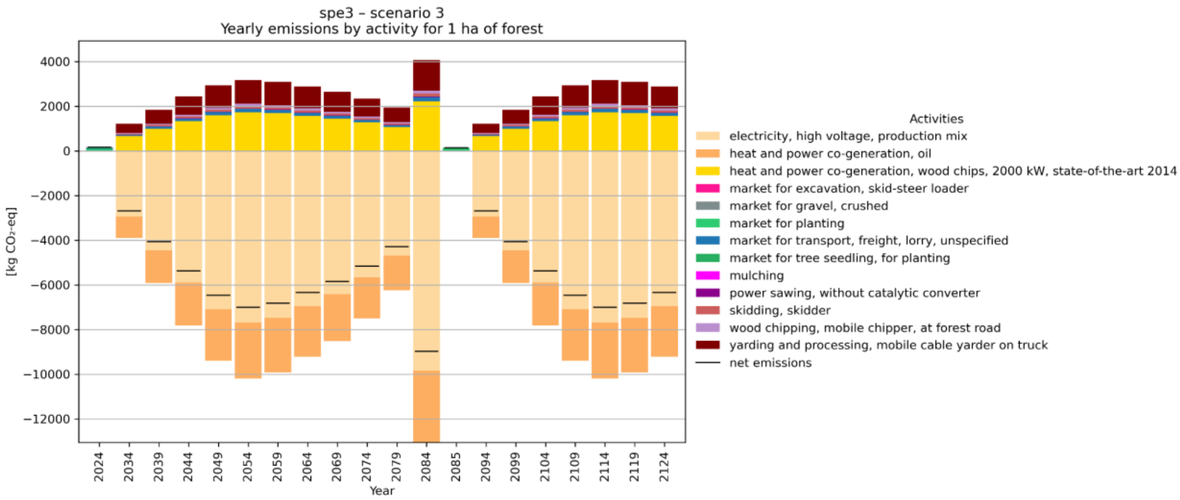

Fig. C 12: *Yearly emissions by activity for 1 ha over 100 years in [kg CO_2-eq/ha] - scenario 3, specie 3*

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