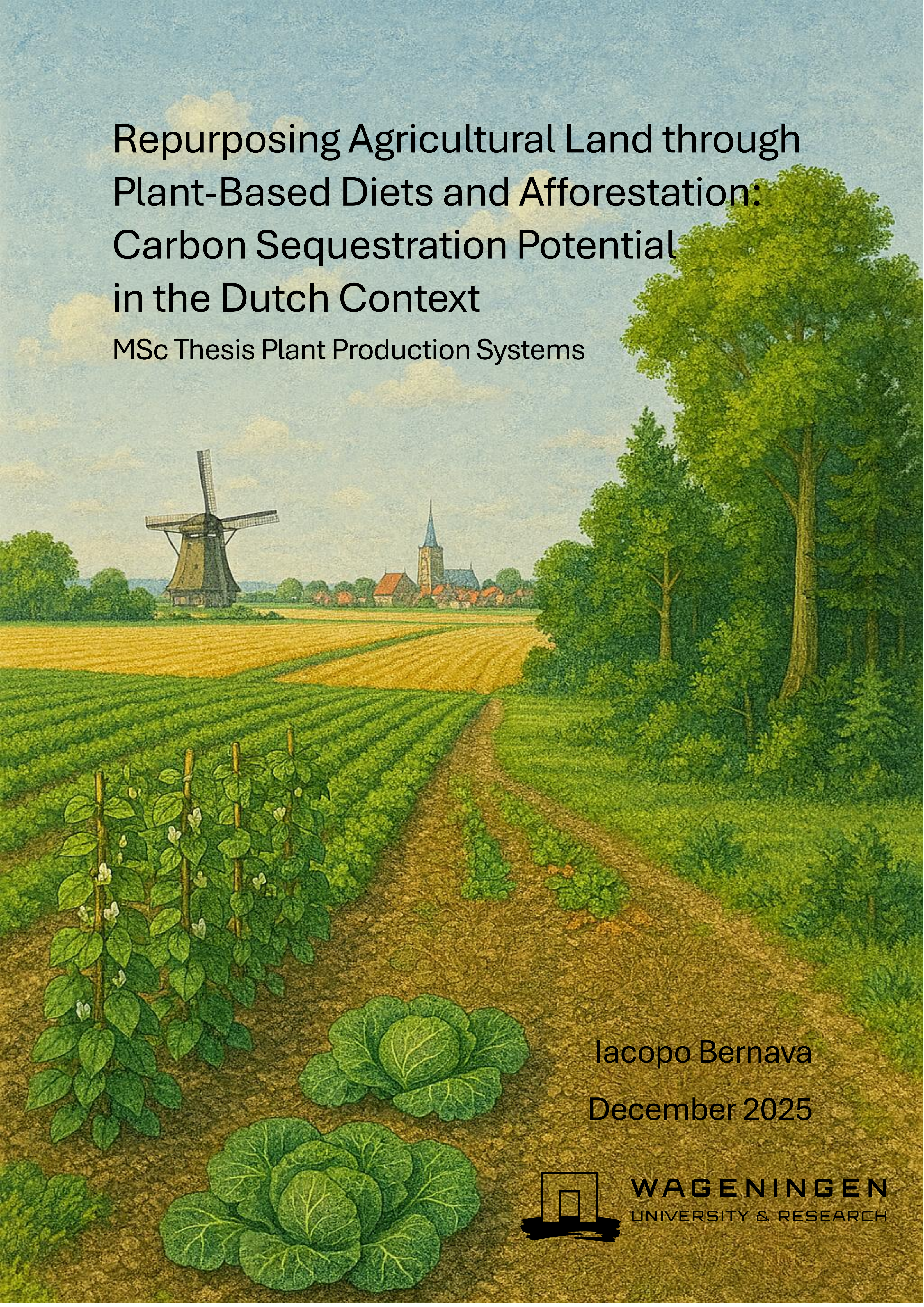

Repurposing Agricultural Land through Plant-Based Diets and Afforestation: Carbon Sequestration Potential in the Dutch Context

MSc Thesis Plant Production Systems

Iacopo Bernava

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Contact office.pps@wur.nl for access to data, models and scripts used for the analysis

Abstract

Transforming food systems is central to climate-mitigation efforts, as agriculture is a major source of greenhouse gas emissions and occupies extensive land predominantly used for livestock and feed production. Shifting toward more plant-based diets can reduce land pressures and free area for ecosystem restoration. This thesis examines the extent to which alternative diets in the Netherlands can reduce national land requirements and enable climate-smart afforestation and quantifies the carbon stocks that could accumulate under different forest management scenarios. The research aims were threefold: (1) to quantify land requirements (ha person^{-1}) of current and alternative diets using evidence from literature; (2) to estimate domestic land sparing under dietary transitions, considering different scenarios for how Dutch agricultural land is allocated to exports versus domestic consumption; and (3) to model carbon sequestration on spared, well-drained mineral soils under two distinct forestry systems one prioritising biodiversity (NB) and the other prioritizing high growth (PB). Land requirements were synthesised from 20 studies. Land sparing was evaluated through two approaches: a national allocation model varying export shares, and a hypothetical self-sufficient EU-27 food system redistributing land demand among member states. Carbon dynamics were simulated using CO2FIX v 3.2 Modell, which represents biomass, soil, and harvested-wood-product pools. Eight afforestation scenarios were developed by combining two forestry managements, two climate projections, and two wood-processing efficiencies. Results indicate that replacing animal-sourced foods with plant-based options reduces land requirements by 32% under flexitarian diets and 44% under vegan diets. Depending on export assumptions, this translates into 0.29–0.58 Mha of spared land (semi-vegetarian/flexitarian) and 0.39–0.79 Mha (vegan). After excluding peatlands (0.20 Mha), 0.09–0.59 Mha remain available for afforestation. Under a self-sufficient EU-27 system and allocation to countries based on equal weight area and population, no domestic land is freed but external land dependence is eliminated. The simulations show that forestry management type is the dominant factor determining carbon sequestration outcomes. Climate projections and product-processing efficiency introduce only minor variations, causing small differences in total carbon stocks relative to the large gap between management types. Under the assumption that domestic land is freed through dietary change, afforestation on this spared mineral soil could sequester between 1.12 and 19.85 million tons of CO2 equivalent per year in the first 25 years, and between 0.81 and 9.76 million tons of CO2 equivalent per year in the 130-year horizon. This mitigation potential is roughly 6% and 1.7% of total annual emissions from the Dutch food system, so it is only a small contribution. However, this is only a small part of the total mitigation potential of dietary shift. If bioenergy, the restoration of peatlands, sequestration on imported land, and the reduced emissions from feed and livestock production are accounted for, the potential mitigation would be much higher.

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Abbreviation glossary

ABP: Animal-Based Proteins
AFOLU: Agriculture, Forestry and Other Land Use
ASF: Animal-Sourced Food
C: Carbon
CSF: Climate-Smart Forestry
EU: European Union
EU-27: 27 member countries of the EU after the United Kingdom's withdrawal in 2020
GHG: Greenhouse Gases
IPCC: Intergovernmental Panel on Climate Change
LCA: Life Cycle Assessment
LU: Land Use
LR: Land Requirements
Mha: Million hectares (10^{10} m^2)
Mt: Million tonnes (10^9 kg)
NB: Nature-Based Scenario
PB: Production-Based Scenario
PBP: Plant-Based Proteins
PHD: Planetary Health Diet

1. Introduction:

1.1 Background

1.1.2 Climate crisis and the role of agriculture

Human-induced climate change, driven by fossil fuel use and land-use change, is unequivocal and already disrupting ecosystems, economies, and societies (Calvin et al., 2023; Mukherji et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) stresses that limiting global warming to 1.5–2°C requires rapid and profound reductions in greenhouse gas (GHG) emissions across all sectors (Calvin et al., 2023).

Agriculture is central to this challenge. While primary agricultural activities emit about 11% of total anthropogenic GHGs, the entire food system—including processing, transport, and consumption—accounts for approximately 14-18 Gt CO_2 eq., roughly one-third of global emissions (Poore & Nemecek, 2018; Crippa et al., 2021). Beyond its emissions, according to Rockström et al. (2025), "food is the single largest cause of planetary boundary transgression," contributing to biodiversity loss, eutrophication, pollution with novel entities, and land degradation.

Agriculture occupies almost half of the world's habitable land, but its use is highly inefficient. Around 80% of agricultural land is devoted to livestock grazing or feed production, yet livestock provides only 17% of global calories and 38% of protein (FAO, 2024; Poore & Nemecek, 2018). This imbalance reflects fundamental energy losses in animal production: feeding crops to animals converts only a small fraction of their caloric and protein content into edible food for humans (Shepon et al., 2016).

Although livestock efficiency has improved, animal-sourced food (ASF) remains more land-intensive than plant-based food (Aleksandrowicz et al., 2016). Consequently, reducing livestock production in favour of plant-based diets represents a highly effective strategy to spare land for other ecosystem services, particularly carbon (C) storage and biodiversity conservation (Wolf et al., 2019).

Historically, livestock have provided nutritious food, traction, and financial security, enabling the development of civilizations and supporting population growth (Hartung, 2013; Randolph et al., 2007). Today, in low-income settings, livestock remain crucial for ensuring adequate micronutrient intake and supporting income generation (Herrero et al., 2013; Randolph et al., 2007). However, in many high-income countries, the consumption of meat and other animal-source foods (ASFs) exceeds recommended levels, contributing to chronic diseases and environmental impacts (Rust et al., 2020; Miller et al., 2022; Liu et al., 2023). Furthermore, despite the high nutrient density of ASFs, there is scientific consensus that well-planned vegetarian and vegan diets can provide adequate nutrition across all life stages and may offer long-term health benefits (Raj et al., 2025; Craig and Mangels, 2009; Phillips, 2005)

1.1.2 Sustainable diets and land sparing potential

A growing body of research shows that diets with lower amounts of ASF substantially reduce environmental impacts compared to current diets. Meta-analyses indicate that vegetarian and vegan diets can halve land use (LU) and greenhouse gas (GHG) emissions relative to current Western diets (Aleksandrowicz et al., 2016). The EAT–Lancet Planetary Health Diet (PHD) provides a framework for healthy and sustainable eating, emphasizing plant-based foods while limiting animal-sourced products (Rockström et al., 2025).

While a small share of animal protein may increase overall land-use efficiency by utilizing by-products and closing nutrient and energy loops (Van Kernebeek et al., 2016), diets rich in plant-based foods consistently perform best across environmental indicators compared with current Western diets (Rockström et al., 2025). Such dietary shifts could release vast areas of agricultural land currently used for livestock and feed production, creating opportunities for ecological restoration and C sequestration (Lal, 2021; Poore & Nemecek, 2018).

1.1.3 Carbon sequestration through afforestation and peatland restoration

Spared land could be repurposed for afforestation or reforestation, which act as natural climate solutions by storing C in biomass and soils (Masera et al., 2003; Nave et al., 2024). Depending on tree species, management practices, and climatic conditions, afforestation can sequester between 5 and 40 t CO_2 ha^{-1} yr^{-1} through above- and below-ground biomass accumulation during the first 20 years after establishment. In Europe, the average sequestration rate is approximately 9.8 t CO_2 ha^{-1} yr^{-1} (Bernal et al., 2018).

Ideally, forest restoration should be designed to maximize C sequestration while maintaining the provision of other essential ecosystem services, such as biodiversity conservation and income generation. A forest management approach that integrates these objectives is referred to as *Climate-Smart Forestry* (CSF, Nabuurs et al., 2017). CSF is defined here as the establishment of forest systems that (i) employ fast-growing tree species with large stem dimensions and (ii) adopt management practices such as periodic thinning and relatively short rotation lengths. These practices are intended to enhance C uptake and economic viability (Nabuurs et al., 2017)

Nabuurs et al. (2017), evaluated the effect of implementing CSF practices in existing EU forests—together with expanding forest area by 150,000 km^2 (approximately a 1% increase compared with the 2022 forest extent). This measure could sequester 95 Mt C yr^{-1}, equivalent to 350 Mt CO_2 yr^{-1} or about 10-12% of total annual emissions of the EU-27(European Commission, JRC, IEA., 2024; European Environment Agency, 2025).Moreover, according to the United Nations Environment Programme, Emission gap report (2024), the Agriculture, Forestry and Other Land Use (AFOLU) sector ranks second among the main sectors in terms of global greenhouse gas mitigation potential, after the energy sector and ahead of industry, transport, and buildings. Within AFOLU, forestry-related measures—such as reduced deforestation, afforestation/reforestation, and improved forest management—account for approximately 70 % of the sector's total mitigation potential.

However, the effectiveness of land-use change for carbon storage is strongly context dependent. Afforestation is an appropriate mitigation measure primarily on well-drained mineral soils, whereas peat soils require fundamentally different interventions. Peatlands store approximately 3.5 times more carbon than mineral soils and hold up to one third of global soil carbon despite covering only 3–4% of the Earth's land surface (Verhagen et al., 2010; United Nations Environment Programme, 2022). When peatlands are drained for agriculture, aerobic conditions cause peat oxidation and release large quantities of CO_2—globally about 4% of anthropogenic emissions

(UNEP, 2022). In the Netherlands, for example, drained agricultural peat soils emit about 14 t CO_2 eq. ha^{-1} yr^{-1} (Verhagen et al., 2010; Van der Poel et al., 2025).

Because these emissions originate from soil C decomposition rather than a lack of tree cover, afforestation does not independently halt ongoing peat oxidation. Instead, rewetting is required to restore anaerobic conditions and stop carbon losses, making it the primary mitigation strategy for peat soils (IPCC, 2014; Liu et al., 2023). The choice of vegetation plays only a secondary role compared with restoring the water table. (Liu et al., 2023). Therefore, while afforestation on mineral soils represents a major natural climate solution, peat soils demand rewetting rather than tree planting. This thesis focuses solely on C sequestration trough afforestation on spared well-drained mineral soils.

1.1.4 Synergies between dietary transition and carbon sequestration

Several studies have assessed the synergies between dietary transitions and C sequestration potential. These studies explore how shifting towards more plant-based diets can spare agricultural land for ecosystem restoration, thereby increasing terrestrial C storage.

Hayek et al. (2021) assessed the C sequestration potential associated with global dietary shifts to the Planetary Health Diet (PHD) and a vegan diet. Their results indicate that the land spared through these transitions could enable natural ecosystem restoration, leading to cumulative sequestration of 320 and 547 $GtCO_2$, respectively, by 2050. An additional 135 and 225 $GtCO_2$ could be sequestered in soils and litter, although these estimates remain highly uncertain.

Similarly, Kozicka et al. (2023) modelled a scenario where 50% of animal-source foods (ASF) are replaced by plant-based alternatives by 2050. They found that deforestation would be halted and 12% of global agricultural land could be freed for afforestation, sequestering 46 $GtCO_2$ between 2020 and 2050 — equivalent to about 1.5 $GtCO_2$ per year, or roughly 10% of total food system emissions (Crippa et al., 2021; Poore & Nemecek, 2018).

Building on the insights of Hayek et al. (2021), Hayek et al. (2024) introduced the carbon intensity indicator (CII), representing the ratio between potential C sequestration and beef productivity, to assess where dietary transitions would be most beneficial. They found that the highest CII values occur on land originally forested, particularly in temperate regions of the Northern Hemisphere, including Northern Europe. Their results suggest that region-specific assessments are needed, as areas with high livestock productivity may not coincide with those offering the greatest potential for C sequestration through restoration.

At national scales, Jones et al. (2023) found that reduced ASF consumption and food waste in Wales could free 0.35 Mha of land, allowing 50–70 $MtCO_2$ to be sequestered by 2030 through afforestation and peatland restoration. This study highlighted the relevance of restoring multiple ecosystems but assumed a closed food system, without accounting for trade. Likewise, Harwatt and Hayek (2019) estimated that reforesting land used for UK animal agriculture could sequester 4.5 $MtCO_2$, equivalent to 12 years of national emissions, while still providing sufficient calories and proteins.

Together, these studies demonstrate that dietary transitions could substantially increase global C sequestration.

1.2 Research gap

Despite these advances, three main gaps remain. First, existing studies simulate only natural ecosystem restoration, without considering alternative approaches such as CSF, which can enhance C stocks while supporting biodiversity and rural livelihoods (Nabuurs et al., 2017). Second, few studies provide region- or country-specific analyses, even though C sequestration potential and livestock productivity vary considerably across regions. Third, some national-scale studies (Jones et al., 2023; Harwatt & Hayek, 2019) assume that food demand directly drives land demand, without incorporating real-world trade dynamics.

Assessing C sequestration at the national scale would therefore help identify where shifts from grazing or feed-crop systems to restoration could deliver the highest climate mitigation benefits. It would also generate policy-relevant insights for designing targeted mitigation strategies.

While comparable analyses have been conducted for Wales and England, no such assessment exists for the Netherlands. Current Dutch studies (Tamsma et al., 2025; Van Dooren et al., 2014; van Dooren & Aiking, 2016; Van Kernebeek et al., 2016) only estimate potential reductions in agricultural LU from lower ASF consumption, without quantifying the corresponding C sequestration potential of the spared land.

1.3 The Netherlands as a case study area

The Netherlands was selected as the study area due to its extensive data availability, including detailed land-use datasets and afforestation yield tables, which enable robust modelling and scenario analysis. The country also ranks among the highest consumers of animal products worldwide—about 242 kg of meat, dairy, and eggs per capita annually, compared to a global average of 112 kg (Miller et al., 2022; Speedy, 2003)—suggesting that dietary shifts toward plant-based foods could substantially reduce land demand for food production.

According to the Dutch National Food Consumption Survey 2019–2021 (RIVM, 2023), the Dutch diet is characterized by substantial consumption of dairy products and substitutes, cereals, and non-alcoholic beverages, while the intake of legumes and plant-based proteins remains limited. Meat and meat products consumption is 92 g per person per day, while fruit and vegetable intake remains below recommended levels (Netherlands Nutrition Centre, 2020). Overall, 43% of total protein intake is plant-based, indicating a continued predominance of animal-derived foods. (Health Council of the Netherlands, 2023). Dutch agriculture is highly specialized in livestock, particularly dairy farming, with cattle milk being the most produced commodity at 14 million tonnes in 2019 (Hospers et al.,2022). Forest cover remains low—around 10–11% of national territory, the second lowest in the EU after Malta (Alterra et al., 2016; Eurostat, 2022)—suggesting a potential for forest expansion and enhanced ecosystem services. Finally, as a high-income country with agriculture contributing only 1.72% to its gross domestic product (World Bank, 2024), the Netherlands is economically well positioned to transition toward a more sustainable food and land-use system without significant economic burden.

Of the Dutch total 4.2 Mha of land, 1.8 Mha are used for agriculture (Statistics Netherland, 2025), while forests and natural areas account for about 0.5 Mha (Statistics Netherlands, 2020), figure 1 provides an overview of the LU. The latest forest inventory reports approximately 0.37 Mha of forest land (Alterra et al., 2016). About 50 % of the agricultural area is grassland, slightly less than half is arable land, and only a small share is used for orchards or greenhouse farming (Statistic

Netherlands, 2022). Dutch agriculture is intensive, with fertile soils, high inputs, and high yields (Reijneveld, 2013). Most soils are sandy or clayey, but a notable portion consists of peat soils (Heinen et al.,2022).

Figure 1 Land use distribution in the Netherlands, totalling approximately 4.15 million hectares. *Farmland occupies about half of the national surface (2.24 Mha) (CBS,2020)*

Peat soils cover about 10% of the country, with 80% used for intensive dairy production (Verhagen et al., 2010) the Netherlands is the country in the EU with the largest share of drained peatlands in agricultural land (15% , Peakinska & Disselhoff; 2024). Historical drainage of these lands increased productivity but caused large CO_2 emissions from peat oxidation—estimated between 4.2 and 5.6 Mt per year (Van der Poel et al., 2025; Verhagen et al., 2010).

The Netherlands is deeply integrated into global trade. According to Statistics Netherlands (2024), the land footprint of Dutch imports is about 43 million hectares—almost 13 times its land area—but most of this LU is associated with re-exports. The virtual land import for domestic consumption is 5.2 million hectares, of which 2.3 million hectares are cropland, 1.7 million are pastures, and over 1.1 million are forests (Statistics Netherlands, 2024). At the same time, a large share of domestically produced food is exported (€42.3 billion, one-third of the total value of Dutch food exports) (Jukema, Ramaekers, & Woltjer, 2025). These trade dynamics make it highly challenging to project the effect of dietary change on domestic land-use change.

1.4 Research aims, objectives, questions, and hypotheses

The overarching aim of this research is to assess the potential for C sequestration through climate-smart afforestation under alternative dietary scenarios in the Netherlands. To achieve this aim, the research pursues three main objectives: first, to quantify the reduction in land requirements needed to feed the Netherland's population under diets with ASF; second, to assess how much land could be spared within the Netherlands as a consequence of reduced land requirement; and third, to estimate the C stocks attainable under different CSF forestry management scenarios in the Netherlands

In line with these objectives, the study addresses the following research questions:

RQ 1. How much would the land requirement for food (ha person^{-1}) decrease following a shift to diets with less ASF in the Netherlands?

Sub-questions:
1.1 What is the current land requirement of the average diet in the Netherlands?

1.2 What are the land requirements of diets with a reduction in ASF ranging from the PHD diet to a vegan diet in the Netherlands?

1.3 How do the land requirements of such diets compare to those in other countries and at the global level?

Hypothesis (H1):

Based on existing literature, the LU required to support a vegan diet is expected to be less than half of the current requirement, while flexitarian, vegetarian, and healthy guideline diets are expected to reduce LU by approximately 30–50% (Aleksandrowicz et al., 2016).

RQ 2. How much land could be spared for afforestation in the Netherlands if the population adopted diets with less ASF?

Sub-questions:

These two sub-questions address the same overarching question but reflect different methodological approaches and assumptions.

2.1 What would be the reduction in domestic LU under scenarios varying in the proportion of Dutch agricultural land allocated to domestic food consumption?

Assumptions: (i) land for domestic consumption decreases proportionally to the land-requirement reduction associated with dietary shifts, implying proportional decreases in both imported and domestic LU for food consumption; (ii) land used for export remains constant.

2.2 What would be the reduction in LU in the Netherlands if EU-27 countries adopted alternative diets and agricultural land were allocated among member states according to both area and population?

Assumption: The EU-27 is fully food self-sufficient, meaning all agricultural production is used exclusively for domestic consumption within the Union, with no imports or exports outside the EU.

RQ 3. How would carbon stocks per hectares in biomass, soil and wooden products develop over time in afforestation systems under different management scenarios?

Sub-questions:

3.1 How much is the total sequestration in 2050 (total C stock minus initial soil quantity) if the afforestation started in 2025?

3.2 How much is the total sequestration in 2135 (total C stock minus initial soil quantity) if the afforestation started in 2025?

Hypothesis (H3):
Afforestation systems are expected to sequester more than 10 t C ha^{-1} during the first 20 years of establishment, consistent with findings from Bernal et al. (2018).

RQ 4 What is the average annual rate of CO_2 sequestration by 2050 and 2135 when the land freed by dietary shifts is used for afforestation?

Assumption: Peatland restoration (0.20 Mha) is prioritised; afforestation takes place only on the remaining spared land.

2 Methodology

2.1 RQ1 Assessing land-requirement of alternative diets

2.1.1 Literature review

To assess the LU implications of alternative diets, a structured literature review was conducted. The objective was to gather data on land requirements (expressed in hectares person^{-1}) for diets with reduced consumption of animal-based products, with a particular focus on the Netherlands.

Literature was searched in Scopus and Web of Science with the constraint filters: peer-reviewed and publication between 2010 and 2025. The following search string was used:

“land” AND (“use” OR “require” OR “footprint”) AND (“livestock” OR “livestock production” OR “livestock consumption” OR “animal based product” OR “animal based protein*” OR “animal sources protein*” OR “meat dairy and eggs” OR “protein transition” OR “plant-based diet*” OR “protein substitution” OR “animal to plant protein*”) AND (“Netherlands” OR “Dutch” OR “Europe*”)***

This search yielded 199 results from Scopus and 485 from Web of Science. The articles went through a two-step selection process. First, title and abstract were screened. Second, the full texts were skimmed. Articles were included when: they were written in English and, they quantify land requirement for food per capita or potential land saving from sustainable dietary shifts. The diet considered had to be either Dutch baselines, or diet with some reduction in animal sourced foods. While the primary focus was on the Netherlands, articles set in broader contexts—such as entire Europe, specific European countries, or global scales—were also considered. This broader inclusion was necessary for the sake of comparison, due to the limited number of Dutch-focused studies, and to the fact that the scenarios assessed in those papers were not perfectly aligned with the research question.

In total, 20 articles met all inclusion criteria and were retained for final review. For each selected study, the following information was extracted: Study region, Dietary scenarios, Land requirement or LU change, Methodology used, Underlying assumptions. The information from these studies is summarized in Appendix 1. Reference management and article selection were supported using Zotero.

The articles presenting land requirements for different dietary scenarios are first summarized. Then, the land requirements from this articles are converted into LU reductions relative to the baseline and integrated with studies that express LU reductions only.

2.1.2 Estimating the land savings

Estimating the potential land savings in the Netherlands resulting from a population-wide shift to plant-based diets is challenging due to the high degree of food trade. A substantial share of food consumed domestically is produced abroad, while a large proportion of Dutch agricultural output is exported. To address this complexity, two complementary approaches were applied.

Approach 1 - Internal land use allocation scenarios, exports vs domestic consumption

This approach captures the uncertainty regarding how changes in national food demand translate into reductions in domestic agricultural LU. Three scenarios were designed to represent alternative assumptions about the share of Dutch agricultural land dedicated to domestic food consumption versus export production. The scenario range therefore reflects the uncertainty surrounding the influence of domestic food demand on internal LU patterns.

1. 100% Export scenario: All agricultural land is dedicated to exports. Dietary changes in the Netherlands do not affect domestic LU.
2. 50% Export scenario Half of agricultural land supports exports and half supports domestic consumption. Dietary shifts partially influence domestic LU. This intermediate situation represents a closer to reality case in which changes in national food demand partially influence internal LU.
3. 0% Export Scenario: All agricultural land supplies the domestic market. Dietary changes directly translate into domestic land savings.

Reductions in agricultural land demand associated with dietary transitions were derived from the literature sources (Section 2.1.1.) Two dietary transitions were considered: From the current diet to a semi-vegetarian/flexitarian diet, and from the current diet to a vegan diet.

For each transition, the average percentage reduction in total LU reported across studies was applied uniformly across the three scenarios.

Land savings were then calculated as:

$$Land\ Savings = Baseline\ LU \times Land\ Reduction\ Factor \times (1 - Export\ Share) \qquad (1)$$

Where:

- The *Baseline LU* is the current agricultural LU in the NL, set as 1.8 Mha, as reported by Statistics Netherland (2025).
- The *Land Reduction Factor* is the proportional reduction in LU associated with dietary change, derived as the mean value from the reviewed studies
- The *Export Share* is the share of agricultural land used for export production (1.0, 0.5, or 0.0 in the respective scenarios). Thus, $(1 - Export\ Share)$ represents the share of land used for domestic food consumption.

This approach assumes that the reduction in land requirements resulting from dietary changes is proportional between domestic and imported (virtual) LU. Consequently, it does not distinguish between land spared internally and land spared abroad. Furthermore, potential changes in trade structure or export composition following dietary transitions are not considered. The approach 1 therefore provides a simplified but transparent framework to approximate the range of potential domestic land savings under different assumptions about the relationship between national food demand and internal LU.

Approach 2 — Reallocation under a Self-Sufficient European Food System
In the second approach, the EU-27 is assumed to operate as a net-zero import–export food system, such that food production and consumption are balanced within the Union. Under this assumption, the reduced total EU land requirement under alternative diets is reallocated among

member states based on two equally weighted criteria: national population size and national land area.

First, the average per-capita land requirement under the alternative diet (obtained from the literature) was multiplied by the EU-27 population (450 million) to estimate the total agricultural land requirement in the EU. The share allocated to the Netherlands was calculated as:

$$LU_{NL} = 0.5 \times LU_{EU} \times \left(\frac{Population_{NL}}{Population_{EU}} + \frac{Area_{NL}}{Area_{EU}}\right) \tag{2}$$

Where:

- LU_{EU} is the total EU agricultural land requirement under the new diet.
- $Population_{NL}$ is 18 million (European Union, n.d.).
- $Population_{EU}$ is 447 million (European Union, n.d.).
- $Area_{NL}$ is 4.15 Mha (CBS, 2020).
- $Area_{EU}$ is 41.01 Mha (Eurostat, n.d.).

This approach provides an alternative estimate reflecting uncertainty in international trade dynamics and offers an upper and lower bound on potential Dutch land savings when the EU is treated as a closed food system

2.2 RQ2 Assessing C sequestration through afforestation

2.2.1 Choice of Model

To assess C stocks under land-use change scenarios, the CO2FIX model (version 3.2) was used. CO2FIX is a stand-level simulation tool designed to estimate C stocks and fluxes over time across different forestry scenarios. The description of the model presented here is based on the official CO2FIX guide (Schelhaas et al., 2004), Liski et al. (2005); and Masera et al. (2003).

Among available tools, CO2FIX was selected because the research question required estimating total forest C stocks across all major pools: living biomass, soil, and harvested wood products. The model can simulate stands composed of single or mixed tree species, incorporating thinning and rotation cycles, which makes it particularly suited for CSF (climate-smart forestry) scenarios. CO2FIX relies on empirical yield data to drive stand development. In the Netherlands, detailed species-specific yield tables are available (Jansen & Oosterbaan, 2018) for a variety of site classes and thinning regimes, which made this model both appropriate and practical for the study.

2.2.2 Model Structure

CO2FIX is a dynamic, multi-cohort model that simulates a homogeneous forest stand of one hectare. A cohort is defined as a group of trees (or other vegetation) of the same species and age. The simulation proceeds in annual time steps over a user-defined period. The model includes six modules: biomass, soil, products, bioenergy, financial, and C accounting.

In this study, only the biomass, soil, and products modules were used. The financial and C accounting modules were excluded because they focus on costs, revenues, and crediting systems, which are outside the scope of this thesis.

The total C stock in the system at time t (t C ha^{-1}) is given by:

$$CT_t = Cb_t + Cs_t + Cp_t \tag{3}$$

Where:

- CT is the total C stored in the whole system
- Cb is the C stored in tree or other biomass
- Cs is the C stored in the soil
- Cp is the C stored in product deriving from logged trees

The broader climate change mitigation effect A is defined as the sum of total stored C, plus avoided emissions from bioenergy use, minus the initial baseline C stock as the formula that follow:

$$A = CT_t + Cbio_t - Cbase \tag{4}$$

Where:

- CT_t is total C physically stored in the system at time *t*
- $Cbio_t$ is the avoided emissions (in C equivalents) due to bioenergy use at time *t*
- $Cbase$ is the C in the baseline i.e the C present at year zero.

The bioenergy module, although relevant for estimating avoided emissions through fossil fuel substitution, was not applied due to difficulties in parameterization and time constraints.

Model accuracy

CO2FIX is a deterministic model, meaning it produces a single trajectory for each simulation. It does not inherently represent natural variability or stochastic events, unless these are explicitly parameterized as special cases. To approximate natural variability, the model documentation recommends using average or median parameter values (e.g., for C content and wood density) and/or performing multiple runs with perturbed inputs to assess the sensitivity of results (Schelhaas et al., 2004).

The accuracy of the biomass module largely depends on the quality and representativeness of the yield tables used as input data. By contrast, uncertainty in the soil C module is greater, as decomposition dynamics depend strongly on parameters such as humification fractions and humus decomposition rates. Nevertheless, the soil component of CO2FIX relies on the Yasso model, which has been parametrized and validated against extensive data sets, including litter bag experiments and long-term soil C chrono sequences across diverse climatic regions and litter inputs (Liski et al., 2005; Peltoniemi et al., 2004). Liki et al. (2005) reported that (I) in southern Finland yasso reproduced average C stocks within approximately ±15% of observational means, (II) litterbag experiments showed that Yasso's climate–decomposition relationships achieved coefficients of determination $r^2 = 0.71–0.80$. (III) validation of Yasso's temporal dynamics showed high accuracy: modelled soil carbon accumulation rates in ageing forests differed from measurements by only ~1 g C m^{-2} yr^{-1}. Given that observed accumulation rates are typically 4–5 g C m^{-2} yr^{-1}, this corresponds to a relatively small deviation.

Biomass module

The total C biomass equals the sum of the C in each cohort. A cohort is defined as a group of trees that share similar characteristics and can be modelled as a single unit. At each time step, the biomass of a cohort is updated as the original biomass plus growth, minus the turnover of branches, foliage, and roots, as well as tree mortality and harvest.

Stem growth is simulated using volume increment data (m^3 ha^{-1} yr^{-1}), typically derived from yield tables. Biomass growth in foliage, branches, and roots is then estimated through allocation coefficients relative to stem growth, which vary over time.

Cohort interactions are modelled through a growth modifier that accounts for competition for stand-level resources. As total stand biomass approaches the maximum carrying capacity, the growth rate of each cohort is progressively reduced until it approaches zero near saturation.

Management interventions are represented by specifying thinning fractions, defined as the proportion of stem volume removed relative to total stand volume. The harvested biomass is then distributed into product categories—logwood, pulpwood, and slash—according to user-defined allocation factors.

Soil Module:

CO2FIX v3.2 represents soil organic carbon using the Yasso model, which simulates annual changes in soil C under well-drained conditions and without stratifying soil layers. In this framework, all litter entering the soil—derived from turnover, natural mortality, management mortality, or harvest residues—is partitioned into three litter categories: non-woody, fine-woody, and coarse-woody material. Because the biomass module does not distinguish between root size classes, fine and coarse root litter is allocated using the branch-to-foliage ratio.

Each litter category decomposes and contributes carbon to five chemical compartments: extractives, celluloses, lignin-like compounds, and two humus pools. Decomposition follows first-order kinetics, with climate-dependent rate modifiers that increase under warmer and wetter conditions and decrease under summer drought. A fixed proportion of carbon lost from each compartment is transferred to the subsequent, more recalcitrant pool, while the remainder is emitted as CO_2. The chemical composition of fresh litter (extractives, cellulose, lignin fractions) and the humification fractions are predefined in the model and differ for conifers vs. broadleaves. A full description of the soil module equations, parameters, and climate response functions is provided in Appendix 3

Initial soil C stocks may either be provided by the user or calculated automatically by running Yasso to equilibrium under pre-afforestation litter inputs and site-specific climate. In this thesis, equilibrium stocks were generated using this built-in procedure.

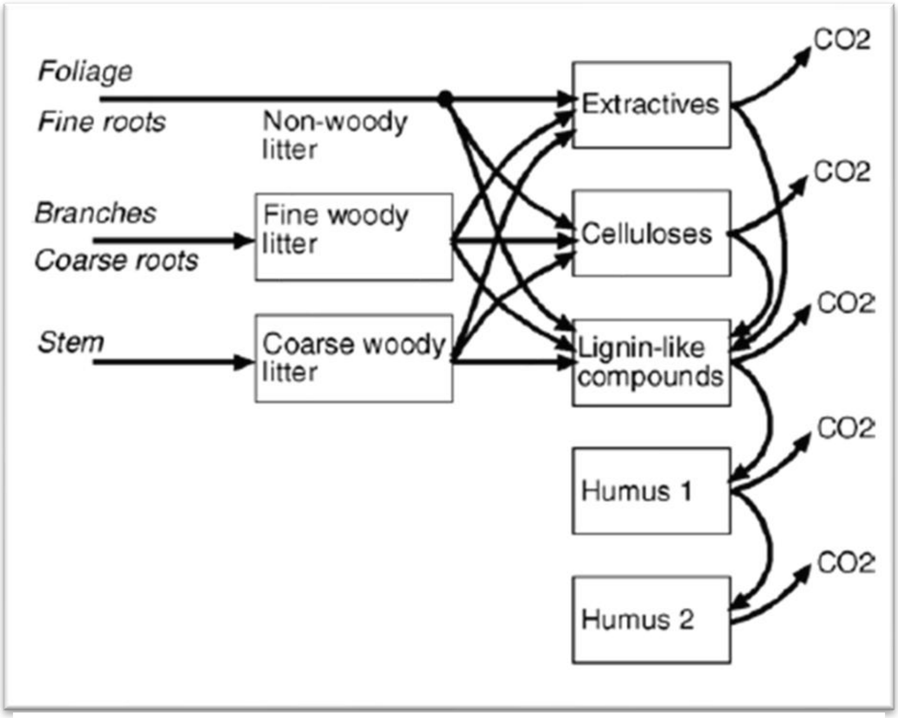

***Figure 2 Flow chart of the soil module. The boxes represent the carbon compartments, and the arrows represents carbon fluxes**. (taken from CO2Fix Model Guide)*

Product module

The products module tracks C after thinning and harvesting. Stem and branch biomass is divided into logwood, pulpwood, and slash according to the fractions specified in the biomass module. Logwood is further allocated to sawn wood, boards and panels, and pulp and paper, while the remainder is directed to firewood. Pulpwood is allocated to boards and panels, and pulp and paper. Each of these “commodities” is subsequently distributed into long-, medium-, or short-term product categories, each with a defined half-life time. At the end of their lifespan, products can either be recycled into other categories, used for energy, or disposed of in a landfill

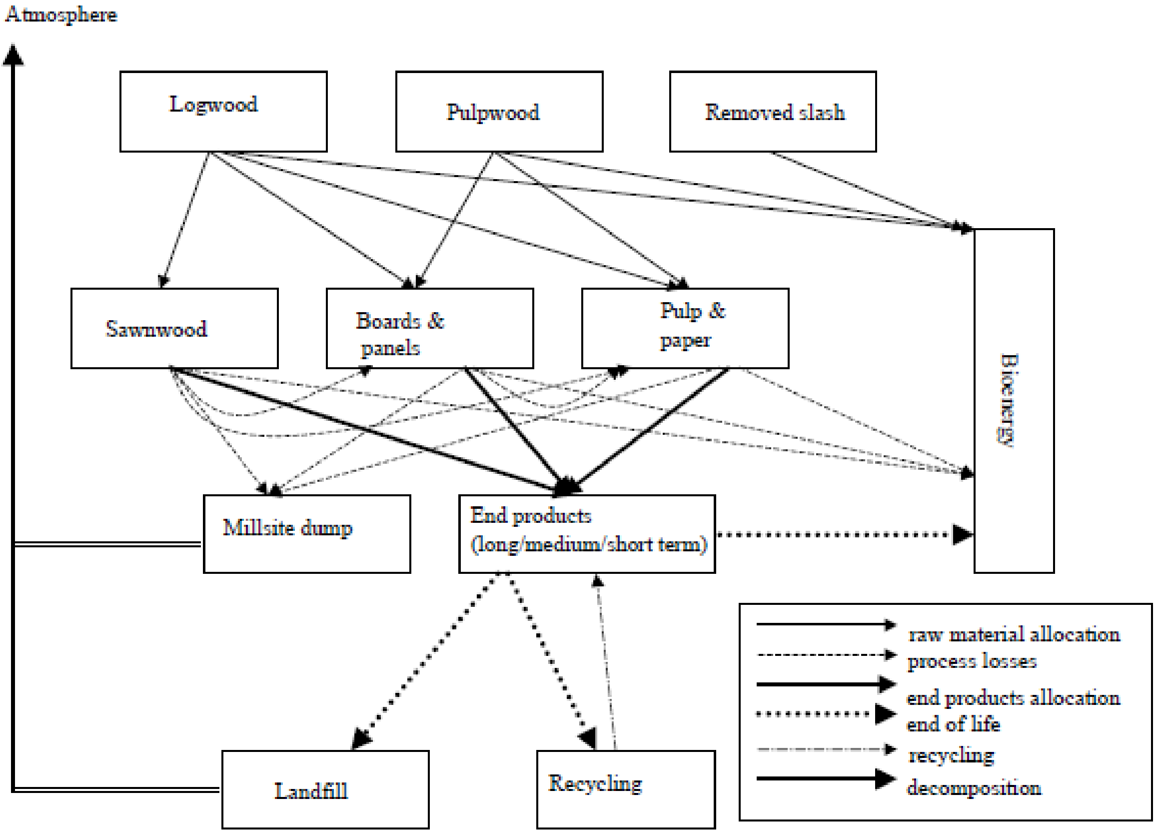

Figure 3. Schematic overview of the wood products module. The boxes represent carbon stocks, while the arrows indicate the transfers of carbon through different stages of the chain, from harvest to final allocation. *(taken from CO2FIX guide)*

CO2FIX provides two default parameter sets for the products module: one assuming high or low processing and recycling efficiency. These parameter sets are based on earlier models developed for the European forest sector (Karjalainen et al., 2002; Eggers, 2002). They differ in the proportion of harvested biomass converted into useful products and in the extent of recycling.

2.2.3 Scenario designs

The simulations cover eight scenarios, differing along three dimensions: forestry type, climatic projections, and product processing and recycling efficiency. Each dimension includes two options.

Forestry type

Two contrasting forestry managements were designed to reflect “extreme” versions of climate-smart forestry (CSF). One emphasizes biodiversity conservation through native species and moderate interventions, while the other prioritizes C sequestration and economic returns by relying on fast-growing, high-yielding species and more intensive management.

- **Nature-based (NB).** This scenario uses a even mixture of three native tree species in the Netherlands: Scots pine (*Pinus sylvestris*), common oak (*Quercus robur*), and birch (*Betula pendula*) (Lust et al., 2000). The stand combines an adaptive conifer, a fast-growing deciduous species, and a slow but persistent long-lived tree. Thinning is moderate, and rotations are long—100 years for pine, 80 for birch, and indefinite for oak. This setup exemplifies CSF with a strong emphasis on biodiversity provision, which is a key objective in both national and international policy agendas (De Knegt et al., 2024; van Strien et al., 2016).

- **Production-based (PB).** This scenario focuses on profitability and C sequestration potential. It employs 50% Douglas fir (*Pseudotsuga menziesii*) and 50% Japanese larch (*Larix kaempferi*), both non-native but widely present in the Netherlands. These species are highly productive, with heavy thinning and short rotations—40 years for larch and 55 years for Douglas fir—resulting in high yields and rapid C accumulation. This scenario illustrates CSF where economic viability and C uptake are prioritized over biodiversity.

Climatic projections

Climatic conditions were parameterized using projections from the *Klimaateffectatlas* (2025). Two contrasting pathways were considered. The Klimaateffectatlas provides hypothetical future climate scenarios developed by KNMI (Royal Netherlands Meteorological Institute), covering the lowest and highest end projections for 2100.

- A **high-impact** scenario, in which climate change effects are more pronounced.
- A **low-impact** scenario, with relatively mild changes.

Including both projections accounts for uncertainties in future climate trajectories and ensures robustness in the results.

Product processing and recycling efficiency

The third dimension concerns the fate of harvested wood. The CO2FIX model offers two default parameter sets for the products module:

- **High efficiency**, with greater conversion of harvested wood into long-lived products and higher recycling rates.
- **Low efficiency**, with lower processing yields and fewer recycling pathways.

2.2.4 Parameters

The parameters were retrieved from different sources, with some requiring substantial adaptation. Table 1 provides an overview of the parameterization for the two forestry variants, followed by a detailed explanation of the adaptations, assumptions, and choices made.

Table 1. Summary of the parametrisation for the two afforestation scenarios, in the CO2FIX Model V 3.2

Parameters	Nature-based (NB) scenario	Production-based (PB) scenario
Tree species	Scots pine (*Pinus sylvestris)* Common oak (*Quercus robur*) Birch (*Betula pendula*)	Douglas fir (*Pseudotsuga menziesi*) Japanese larch (*Larix kaempferi*)

Rotation length (Years)	100 pine, 80 birch, indefinite oak	40 larch, 55 Douglas fir
Thinning regime	Moderate thinning (except birch heavy thinning)	Heavy thinning
Stem growths (m^3 ha^{-1} yr^{-1})	Yield tables from (Jansen & Oosterbaan, 2018) Site class III, moderate thinning Increment reported divided by three	Yield tables from (Jansen & Oosterbaan, 2018) Site class III, heavy thinning Increment reported is divided by three
Carbon content in the wood (tC tDM^{-1})	0.48 angiosperms, and 0.50 for gymnosperms(Thomas & Martin, 2012)	0.48 Angiosperms (Thomas & Martin, 2012)
Wood density (t DM m^{-3})	0.42 Scots pine, 0.51 Birch, 0.58 Quercus (IPCC, 2003, p. 3.171)	Larch 0.49, Fir 0.45 (IPCC, 2003, p. 3.171)
Growth allocation to foliage, branches and roots factors (dimensionless)	Adapted from the Case studies integrated to the CO2FIX guide	Adapted from the Case studies integrated to the CO2FIX guide
Maximum above ground biomass in the whole stand MAGB (tDM ha^{-1})	300 in oak mixed system (Meyer et al., 2021)	400 (assuming a ratio bove ground biomass/ stem biomass of 1.15) and considering a maximum stem volume of 708 m^3 ha^{-1}.
Competition growth modifiers relative to MAGB (dimensionless)	See appendix 5	See appendix 5
Thinning fractions (dimensionless)	Yield tables from Jansen & Oosterbaan (2018) Site class III, moderate thinning	Yield tables from Jansen & Oosterbaan (2018) Site class III, heavy thinning
Harvest allocation factors (dimensionless)	Used literature with adaptation.	Used literature with adaptation.
Monthly average temperature (°C)	Data are referred to Ede, Gelderland and taken from Klimaateffectatlas (2025)	Data are referred to Ede, Gelderland and taken from Klimaateffectatlas (2025)
Monthly precipitations (mm)	Data referred to Gelderland and taken from Klimaateffectatlas (2025)	Data referred to Gelderland and taken from Klimaateffectatlas (2025)
Initial soil C (t ha^{-1})	92 corresponding to a SOM fraction of 3.5% (A. Reijneveld et al., 2009). At 1.3 t ha^{-1} bulk density, and 0.35 cm depth.	92 corresponding to a SOM fraction of 3.5% (A. Reijneveld et al., 2009). At 1.3 t ha^{-1} bulk density, and 0.35 cm depth.
Product parameters	Taken grom CO2FIX's set of default parameters See appendix 7 for details	Taken grom CO2FIX's set of default parameters See appendix 7 for details

Biomass module

Initial living biomass C

Set to 0 because simulations start from afforestation on ex-agricultural land with no standing trees at *t=0*. Soil C is not zeroed here; it is initialised in the Soil module.

Stem growth

Stem growth was derived from Dutch yield tables (Jansen & Oosterbaan, 2018), which provide annual stem volume increments (m^3 ha^{-1} yr^{-1}) by site class and thinning regime. Site class III (medium fertility) was chosen, as land likely to be spared from agriculture is of medium rather than prime quality. Thinning regimes differ: NB scenario uses moderate thinning (except for birch, for which only heavy thinning tables exist), while PB scenario uses heavy thinning. Since the yield tables report growth data for trees in monoculture, the annual increment was divided by two in the NB scenario (two tree species) and by three in the PB scenario (three species) to account for the reduced density of each species within mixed stands. The model does not simulate interactions between tree species; therefore, potential interspecific effects that could modify species-specific increments are outside the scope of this study and are considered absent.

Wood densities and carbon fractions

Species-specific wood densities values were taken from IPCC (2003) (see Table 1). C fractions were set at 0.50 for conifers and 0.49 for deciduous species (Thomas & Martin, 2012).

Growth allocations to foliage branches and roots

Allocation factors were taken from CO2FIX case studies integrated into the guide (Schelhaas et al., 2004). Where available, case studies with the same species were used (Scots pine, oak); otherwise, analogues were applied (oak as proxy for birch; Norway spruce for larch and fir). Allocation factors are age-specific and relative to stem growth. To harmonize them with the stands in this study, growth tables from the case studies were compared with the yield tables applied here, and the allocation curves were adjusted to align key features, such as matching peak stem growth with minimum foliage allocation.

Competition among cohorts

Growth is modified relative to total stand biomass using a function $f\ (B_{total}/B_{max})$ that reduces growth as the stand approaches maximum biomass. This requires defining B_{max} for the stand The function is interpolated from user-provided points (see Appendix 5). For the NB scenario, Bmax was set at 300 t DM ha^{-1} (oak mixed system; Meyer et al., 2021). For the PB scenario, Bmax was set at 415 t DM ha^{-1}, calculated from Douglas fir maximum stem volume (708 m^3 ha^{-1} at 120 years, Jansen & Oosterbaan, 2018) and assuming this species defines the stand maximum biomass.

Allocation factors of harvested stems branches to logwood pulp and paper, and slash

Due to the lack of detailed data, allocation factors were set manually based on empirical rules. These rules were adapted from Alterra et al. (2005), Heräjärvi and Junkkonen (2004), Koynov et al. (2025), and Koynov et al. (2021). They define the fractions of wood allocated to logwood, pulp and paper, and slash as a function of stem diameter, which was obtained from the yield table (Jansen & Oosterbaan, 2018).

For stems, a fixed proportion (0.15) was consistently allocated to slash, while the remaining volume was distributed between logwood and pulpwood depending on stem diameter. According to the literature, stems are not typically used for logwood until they reach a diameter of 10 cm. At this threshold, 0.05 of the fractions was allocated to logwood, increasing progressively up to 0.60 when the diameter reached 60 cm. These parameters are species-specific, with diameter values derived from yield tables corresponding to the age of each cohort. The midpoints used for allocation are reported in Appendix 6.

For branches, different allocation patterns were applied depending on species group. In long-rotation angiosperms, a larger proportion of branches was allocated to logwood, whereas in short-rotation conifers and angiosperms the allocation was considerably lower, reflecting the smaller branch size relative to stems. Further details are provided in Appendix 6. All slash was consistently allocated to the soil compartment.

Soil module

For the soil module, the required inputs are: (1) growing-season precipitation [mm] (assumed April to October), (2) degree days [°C] as the sum of daily mean temperatures above 0 °C, and (3) growing-season potential evapotranspiration (PET) [mm]. CO2FIX calculates PET with the Thornthwaite method from monthly mean temperatures and the indicated growing-season months. Degree days are also computed by the model from monthly mean temperatures.

Monthly climate data (temperature and precipitation) are based on Ede, Gelderland, NL, used as a proxy for average Dutch conditions. According to the Klimaateffectatlas (2025) Ede represents more or less an intermediate point in the NL, where southwest is warmer and the northeast is cooler.

Monthly patterns of temperature and precipitation were obtained from Climate Data.org (2025) and adjusted using projection scenario from Klimaateffectatlas (2025). The Klimaateffectatlas provides hypothetical future climate scenarios developed by KNMI (Royal Netherlands Meteorological Institute), covering the lowest and highest end projections for 2100. To ensure consistency, the monthly time series from Climate Data.org were rescaled so that their annual means matched the Klimaateffectatlas projections, while still preserving the original monthly pattern. Concretely, the adjustment involved calculating the annual average from the Climate Data.org series, dividing the Klimaateffectatlas annual value by this average to obtain a scaling factor, and then multiplying each monthly value by this factor.

Soil initial C was calculated by assuming assumed 3.5% of Soil Organic Matter (SOM) following. (A. Reijneveld et al., 2009) for sandy/loess and marine clay soils. The organic horizon depth was set to 35 cm and bulk density to 1.3 t m^{-3}, yielding a soil mass of 3,500 m^3 ha^{-1} × 1.3 t m^{-3} = 4,550 t ha^{-1}. At 3.5% SOM, this corresponds to ≈160 t SOM ha^{-1}. Converting SOM to soil organic carbon (SOC) using the van Bemmelen factor (0.58; Heaton et al., 2016) gives ≈92 t C ha^{-1} .

CO_2FIX requires the initial soil C to be distributed across the three litter pools and five decomposition pools. The "Calculate initial carbon button" was therefore used to compute automatically the quantities to each pool. This tool requires constant annual litter inputs (foliage, branches, roots, stems) for the period prior to the simulation. Inputs were tuned iteratively by comparing the resulting equilibrium SOC with the ≈92 t C ha^{-1} target and adjusting values until matched. Given the pre-simulation LU (cropland/grassland), foliage inputs were emphasized.

Final annual litter inputs

- Higher-end climate scenario: foliage 3.6 t ha^{-1} yr^{-1}, branches 0.4 t ha^{-1} yr^{-1}, roots 0.46 t ha^{-1} yr^{-1}.
- Lower-end climate scenario: foliage 4.0 t ha^{-1} yr^{-1}, branches 0.4 t ha^{-1} yr^{-1}, roots 0.50 t ha^{-1} yr^{-1}.

These inputs yield an equilibrium total SOC of ≈92 t C ha^{-1}, used as the model's initial soil C stock.

Product module

As mentioned above two sets of default parameters are employed in this thesis

1. High processing and recycling efficiency system
2. Low processing and recycling efficiency system.

To fully explore the potential outcomes, both the high- and low-efficiency scenarios were applied to both the Nature-based and Production-based forestry types, and both climate projections; thereby capturing the uncertainty associated with the product module across different management strategies and about future climate.

2.2.5 Final output

The final outputs are the total C stocks accumulated across the entire system after a 25 and 130-year simulation period. These results are generated for eight scenarios derived from a full-factorial combination of three dimensions: forestry type, climate projection, and product efficiency. The scenarios are summarised in Table 2.

Table 2 Overview of the eight scenarios generated from the full-factorial combination of forestry type, climate projection, and product efficiency.

Scenario ID	Forestry Type	Climate Projection	Product Efficiency
1	Nature-based	Low-impact	High
2	Nature-based	Low-impact	Low
3	Nature-based	High-impact	High
4	Nature-based	High-impact	Low
5	Production-based	Low-impact	High
6	Production-based	Low-impact	Low
7	Production-based	High-impact	High
8	Production-based	High-impact	Low

A full-factorial design was chosen rather than pre-selecting specific combinations (e.g., PB with high efficiency and NB with low efficiency). This approach was adopted because there is considerable uncertainty surrounding: (I) wood processing and recycling pathways (II) future climate conditions. By simulating all possible combinations, a clearer and more robust picture of the potential range of outcomes can be obtained, avoiding assumptions about how different forestry strategies might align with future processing efficiencies and climatic conditions.

3 Results

The results are divided into three sections. Section 3.1 analyses land requirements under current and alternative dietary scenarios in the Netherlands and estimates potential land saving. In Section 3.2, the results of the afforestation modelling are shown, including the estimated C stock per hectare. Section 3.2 presents the afforestation modelling results in terms of C stock per hectare. In Section 3.3, the two previous components are integrated to estimate the total amount of C that could be sequestered through afforestation on the land spared if the Dutch population adopted plant-based diets.

3.1. Land requirements & land use reduction with protein transition

In this section, the results of the literature review on LU under plant-based and reduced-animal diets are presented, providing a preliminary answer to the research questions. The results are organised into four parts. In Section 3.1.1, data from studies reporting land requirements for the Netherlands are introduced. In Section 3.1.2, these findings are compared with data on land requirements at the global level and in other European countries. Section 3.1.3 presents evidence on LU reductions in the Netherlands, globally, and in other countries. Finally, in Section 3.1.4, the potential land savings associated with dietary shifts are estimated. All relevant data extracted from the reviewed articles are summarised in Table 1 and Table 2 of the Appendix 1.

3.1.1 Land requirements in the Netherlands

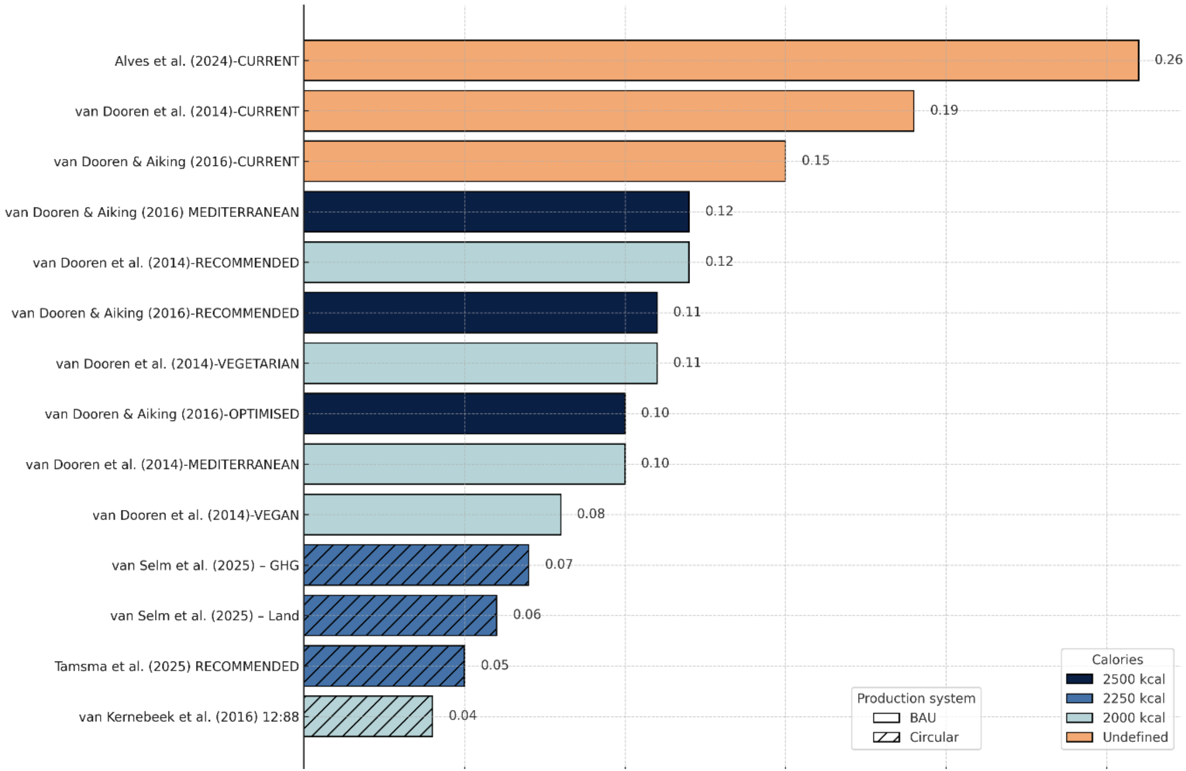

figure 4 Land requirement per capita (ha person $^{-1}$) of diets in the Netherlands across reviewed studies.
“Recommended” refers to the Voedingscentrum diet; “Optimised” denotes a modelled land-use-minimised diet. “12:82” represents the animal-based to plant based ratio.

This subsection presents data from studies that estimate the land required to meet the food demand of the Dutch population under current diet diets with reduced animal-source foods (ASF).In total, five articles were identified. The results are shown in figure *4*.

The diets considered include: the current diet, the recommended diet by the Dutch Nutrition Centre *Voedingscentrum* (hereafter *Recommended*), the mediterranean diet, the vegetarian diet, the vegan diet, and a set of optimisation diets. The latter are not commonly known dietary patterns, but computed diets constructed (in the related studies) to optimise specific factotrs. All alternative diets show a reduction in ASF compared to the baseline. This reduction ranges from a moderate decrease in the Recommended diet, where meat consumption is reduced by 25% and compensated by higher intakes of legumes, vegetables, and fruits, to the complete exclusion of ASF in the vegan diet. Table 3 provides a brief overview of the composition of all diets considered in this report. It is important to note that all studies considered business-as-usual production systems to estimate LU, except for van Selm et al. (2025) Tamsma et al. (2025) and van Kernebeek et al. (2016), who assumed fully circular food systems in which co-products and human-inedible biomass are fed to animals to minimise LU

As a general overview the result shows a reduction in LU parallelly to the reduction in ASF in diet, but the biggest reduction is achieved by including circularity practices.

Focusing on the details: for the baseline, the land footprint of current Dutch diets ranges between 0.26 and 0.15 ha per person (Alves et al., 2024; van Dooren et al., 2014; van Dooren & Aiking, 2016). For alternative diets, van Dooren & Aiking (2016) reported LU (ha person^{-1}) of 0.12 for the Mediterranean diet, 0.11 for the Recommended diet, and 0.10 for the Optimised diet. Similarly, van Dooren et al. (2014) found 0.12 for the Recommended diet, 0.11 for the vegetarian diet, and 0.08 for the vegan diet (figure4).

Van Kernebeek et al. (2016) van Selm et al. (2025) and Tamsma et al. (2025) modelled land requirements in circular, closed Dutch food systems—meaning no imports or exports and full domestic sourcing. Van Kernebeek et al. (2016) found a U-shaped relation between the animal-to-plant protein ratio (ABP:PBP) and LU, with the minimum (0.04 ha person^{-1}) at a 12:88 ratio. This indicates that the lowest land requirement was not achieved with a vegan diet but with a small inclusion of animal products, as animals can upcycle unavoidable crop by-products into food without requiring additional land. Van Selm et al. (2025) assesed how different residual biomass streams—specifically food loss, food waste, and agricultural by-products—should be optimally used in circular food systems found a land requirement of 0.07 and 0.06 ha person^{-1} when the model was optimizing respectively GHG emissions and LU. Tamsma et al. (2025) examined the effect of different levels of provincial food self-sufficiency on LU under the Dutch recommended diet and found a similar land requirement of 0.05 ha person^{-1} in the scenario without trade limitations among provinces.

In summary, van Selm et al.(2025), Van Kernebeek et al. (2016) and Tamsma et al. (2025) reported the lowest land requirements when food systems were optimised for circularity. When considering only dietary shifts without circular optimisation, the vegan diet in van Dooren et al. (2014) required the least land.

Table 3 Overview of the diet considered in the included literature studies

Diet	Articles	Main Characteristics
Current	Alves et al. (2024);van Dooren et al., (2014); Dooren & Aiking (2015)	Contains high consumption of dairy products and beverages, moderate intake of cereals, vegetables, fruits, meat, and eggs, and very low intake of legumes. Overall, it reflects a mixed diet with substantial animal-based foods
Recommended	Tamsma et al. (2025); Van Dooren et al., (2014)	Recommended by Dutch Nutrition Centre. Compared to the current Dutch diet contains more fruit, vegetable and legumes. Less refined sugar, meat and fats.
Mediterranean	Dooren & Aiking (2015); van Dooren et al., (2014);	Entails high consumption of vegetables, pulses, fruits, and cereals, moderate to high fish intake, predominantly unsaturated fats, limited dairy and low meat consumption.
Vegetarian	van Dooren et al., (2014)	Excludes fish and meat.
Vegan	van Dooren et al., (2014)	Excludes fish, meat, dairy, and eggs.
Optimised	Dooren & Aiking (2015)	Increases fruits, vegetables, and legumes, slightly reduces meat, and no cheese. Computed to satisfy three objectives: nutritional adequacy, least GHG emissions , and cultural acceptability.
Land Optimisation **(circularity)**	Van Kernebeek et al (2015)	Computed using only products from the Netherlands. The study show the effect of modifying the animal-based to plant-based protein (ABP/PBP) ratio on land use.
Planetary health diet (PHD)	Aznar de la Riera et al. (2025); Lauk et al.(2022)	Guidelines developed by the EAT-Lancet Commission. Designed to be culturally appropriate and sustainable. It entail a decrease in anima-based protein, and saturated fat. With an increase in fruits vegetables, legumes and nuts.
Flexitarian	Bunge et al. (2024)	Diet where 50 % of ASF (relative to the Swedish diet) are replaced with plant-based foods
Austrian Nutrition Society	Lauk et al. (2022)	Recommended diet by the Austrian Nutrition Society, characterised by low share of meat but a high level of dairy products.

recommended (ANS)		
Vegan Whole-food (Vegan WF)	Bunge et al. (2024)	Replacement of all ASFs with PB whole foods such as legumes, nuts, grains, fruit and vegetables.
Vegan PB-Alternatives (Vegan Alt.)	Bunge et al. (2024)	Replacement of all ASFs by commercially available Plant-based processed analogues mimicking ASFs.

3.1.2 Comparing land requirements across global and European data

In this subsection, figures about the Netherlands are compared with land requirements reported for international and other national contexts. Figure 5 and 6 presents all the land requirement values together.

Baselines

The baseline LU in the Netherlands ranges between 0.15 and 0.26 ha per person(Alves et al., 2024; Van Dooren et al., 2014; van Dooren & Aiking, 2016), which is comparable to the European average dietary LU of 0.23 ha per person reported by *Westhoek et al.* (2011). However, it is substantially lower than the 0.91 ha per person estimated for the average European diet by *Belgacem et al.* (2021). The latter presents LU values that are clear outliers compared to those reported by other studies across different contexts.

Compared to other European countries, the Dutch baseline is on the lower end. For example, estimates for Sweden range between 0.26 and 0.35 ha per person (*Bunge et al.*, 2024; *Röös et al.*, 2018), while Austria shows an average of 0.35 ha per person (*Lauk et al.*, 2022). These differences likely reflect variations in national yields per hectare and dietary patterns, particularly regarding the consumption of ASFs.

At the global scale, the data diverge more significantly. *Röös et al.* (2017) estimated a global food land requirement of 0.61 ha per person, derived by dividing the total global agricultural land area (approximately 5 billion ha; of which 1.5 billion ha is cropland and 3.5 billion ha is pasture and meadows) by the world population (8.2 billion people).

Plant-based Diets

The land requirements outside the Netherlands for PB diets is generally higher, following a similar trend as the baselines beyond the Dutch context.

At the global scale, Röös et al. (2017) found that switching to a fully plant-based diet would require 0.25 ha per person, which is notably higher than the 0.08 ha per person estimated for the Netherlands by van Dooren et al. (2014). However, compared to the global baseline of 0.63 ha per person, this represents a more substantial reduction.

At the European level, the land requirements of plant-based diets are generally higher than those reported in Dutch studies, but the reductions relative to the respective baselines vary. Westhoek et al. (2014) found that halving the consumption of animal-sourced foods (ASF) in Europe leads to a LU of 0.17 ha per person, compared to a baseline of 0.23 ha per person, which represents a smaller reduction than that observed in the Dutch studies. Bunge et al. (2024) and Röös et al. (2018) focused on Sweden and reported somewhat inconsistent results. The former estimated a baseline of 0.34 ha per person and calculated that substituting 50% of meat with legumes would reduce this to 0.26 ha per person. The latter, starting from a baseline of 0.26 ha per person, found that flexitarian, vegetarian, and vegan diets would require 0.20, 0.18, and 0.16 ha per person, respectively. Lauk et al. (2022) analysed Vienna's food system and found that its baseline LU is 0.35 ha per person, which decreases to 0.23 ha for the Planetary Health Diet (PHD), 0.20 ha for the vegetarian diet, and 0.17 ha for the vegan diet.

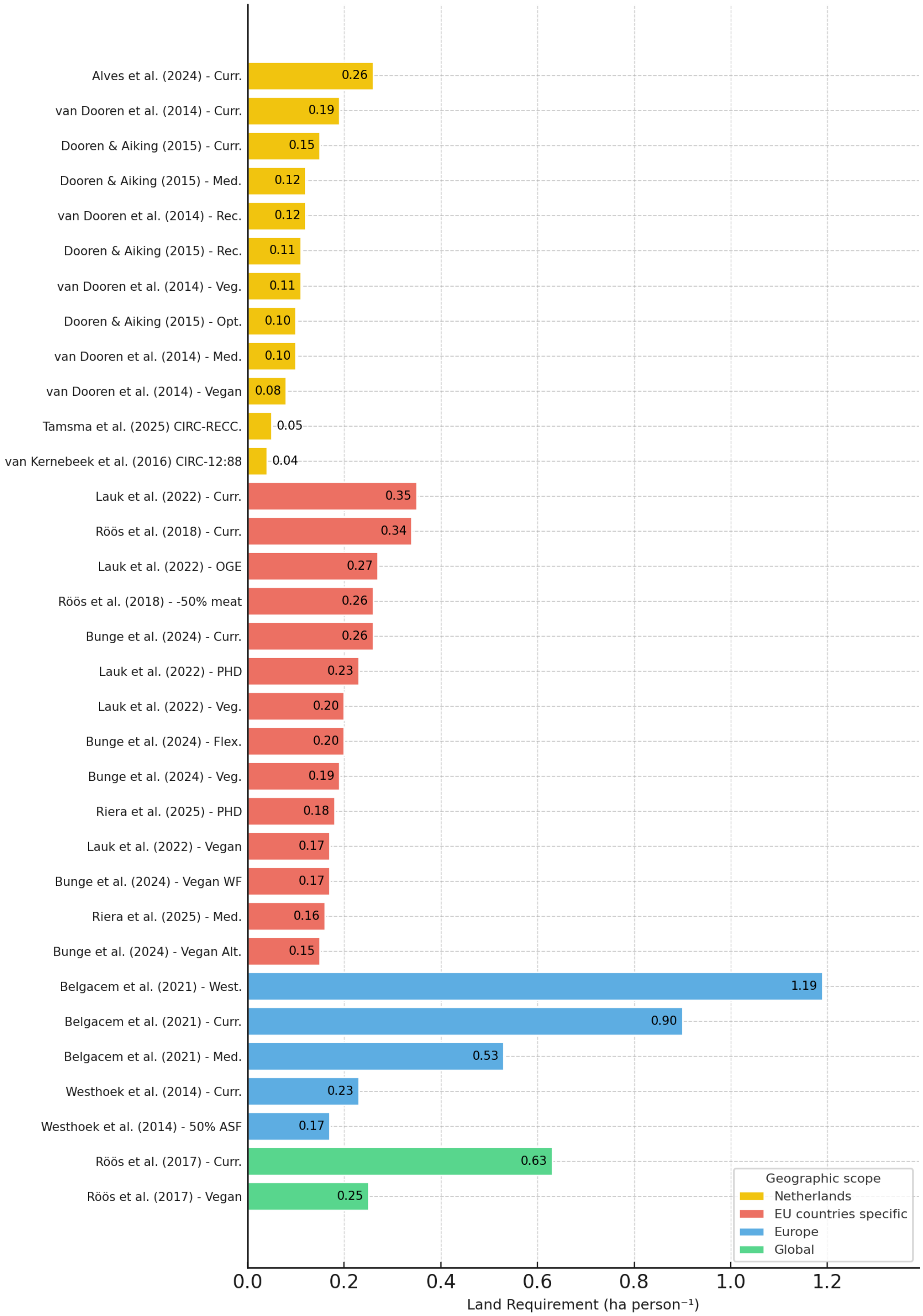

Figure 5 Comparison of Land requirement per capita (ha person $^{-1}$) of different diets across European and global studies. *"Veg" denotes vegetarian diets. PHD represents the planetary healthy diet. For full explanation of the diets refer to table 3.*

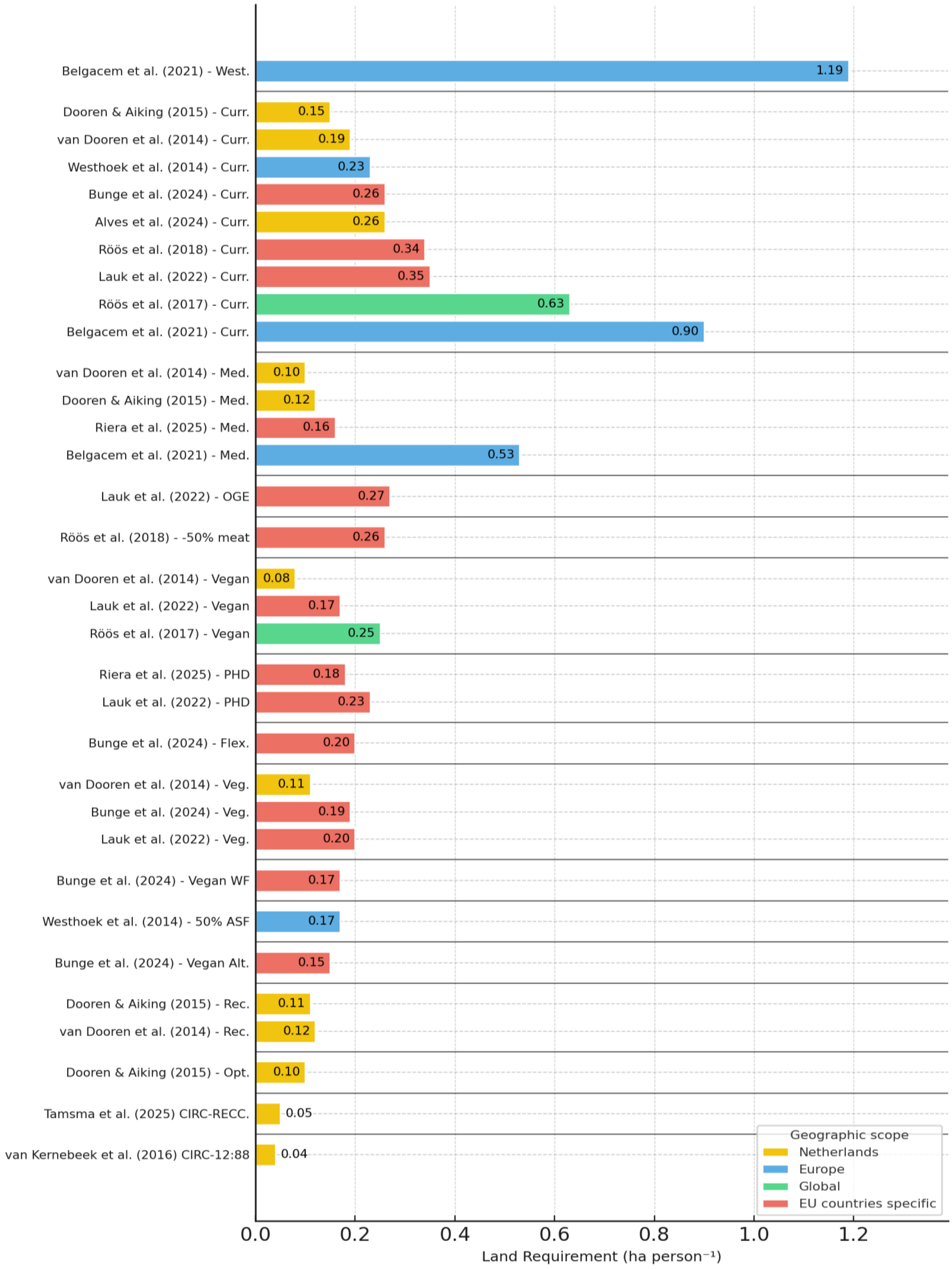

Figure 6 Comparison of Land requirement per capita (ha person $^{-1}$) clustered per diet type across European and global studies. “Veg” denotes vegetarian diets. *PHD represents the planetary healthy diet. For full explanation of the diets refer to table 3.*

3.1.3 Land use reductions overview

The literature shows that shifting towards more plant-based diets can substantially reduce agricultural LU, though the extent depends on the baseline diet, the scale of change, and regional context. Table 4. summarizes estimated reductions across studies and regions.

In the Netherlands, studies indicate considerable potential for land savings. Van Dooren et al. (2014) estimate that moving from the current diet to semi-vegetarian, vegetarian, or vegan patterns could reduce LU by 42%, 53%, and 58%, respectively. Van Kernebeek et al. (2015) report reductions of 21–40% when decreasing animal protein from 60% to 40% or less, with the highest reduction (40%) at a 12:82 protein ratio rather than full veganism, due to circularity assumptions. Tamsma et al. (2025) project a 46% reduction when combining the Dutch recommended diet with circular practices.

Across Europe, reductions range between 15% and 60%. Westhoek et al. (2014) estimate a 26% reduction from halving animal-sourced food, while Daas et al. (2025) find 25% for a moderate protein shift. Balan and Trasca (2024) report smaller effects for Romania (3–9%) due to lower baseline meat intake.

Globally, reductions vary widely. Philippidis et al. (2021) project an 8% decrease when adopting the Planetary Health Diet by 2050. Aleksandrowicz et al. (2016) found 13–77% depending on the degree meat and ASF of replacement, while Simon (2024) reports up to 91% reduction with circular optimization.

Overall, the more plant-based and circular the diet, the greater the LU reduction.

Table 4 Reported reductions in agricultural land use (LU) resulting from dietary transitions across regions and studies. *The compositions of the diet considered are reported in table 3.*

Geographical scope	Study	Dietary transition (from → to)	LU reduction (%)	Notes
NL	Van Kernebeek et al., 2015	60:40 → 40:60 (ABP:PBP)	21	Assuming circularity also in the baseline
NL	Dooren & Aiking, 2015	Current → Optimised (flexitarian)	32	
NL	Van Kernebeek et al., 2015	60:40 → 00:100	30	Assuming circularity also in the baseline
NL	Van Kernebeek et al., 2015	60:40 → 12:82	40	Assuming circularity also in the baseline
NL	Van Dooren et al., 2014	Current → Semi-vegetarian	42	
NL	Tamsma et al., 2025	Current → Circular food system + Recommended diet	46	
NL	Van Dooren et al., 2014	Current → Vegetarian	53	

NL	Van Dooren et al., 2014	Current → Vegan	58	
Europe and Central Asia	Chen et al., 2022	Current to PHD	15	
Europe	Daas et al. 2025	Current to 52:48	25	
Europe	Westhoek et al., 2014	Current to halveing ASF	26	
Europe	Simon et al, ,2024	60:40 to 40:60	60	Along with circularity practices
Global	Philippidis et al. 2021	2050 projected to PHD	8	
Global				
Global	Aleksandrowicz et al. 2016	Current to meat and dairy partially replaced	13-42	
Global	Aleksandrowicz et al. 2016	Current to vegetarian	27-66	
Global	Aleksandrowicz et al. 2016	Current to vegan	44-77	
Global	Wolfran Simon, 2024 (ch. 5)	Current to land use optimisation	91	Entails a chang in diet and circularity practices
Romania	Balan& Trasca, 2024	Current to halving ASF	3	
Romania	Balan& Trasca, 2024	Current to vegan	9	
Denmark	Prag & Henriksen, 2020	Current to 50& PHD implementation	20	
Sweden	Röös et al. 2018	Current to halving meat	23	
Sweden	Bunge et al., 2024	Current to flexitarian	24	
Sweden	Bunge et al., 2024	Current to vegetarian	27	
Sweden	Bunge et al., 2024	Current to vegan	35-42	
Vienna	Lauk et al. 2022	Current to PHD	26	
Vienna	Lauk et al. 2022	Current to Vegetarian	44	
Vienna	Lauk et al. 2022	Current to vegan	53	
Germany	Helander et al., 2021	Current to PHD	43	
Germany	Helander et al., 2021	Current to low dairy vegetarian	48	

3.1.3 Estimating the land savings

Two approaches were applied to estimate potential land savings in the Netherlands resulting from a dietary shift toward plant-based diets. The first simulates varying degrees of how food demand influences land demand, while the second assumes a self-sufficient European food system where land is reallocated among EU member states.

Approach 1 (Explained in Methods section 2.1.2) indicates that under a flexitarian or semi-vegetarian transition, internal land sparing in the NL range from 0.32 to 0.64 Mha, while a vegan diet results in 0.44–0.88 Mha. The area potentially available for afforestation excludes approximately 0.2 Mha of peat soils (Liu et al., 2023; Verhagen et al., 2009).

Approach 2 shows that, if the EU reduces animal-source food (ASF) consumption by 50% within a self-sufficient food system, the Netherlands would not experience domestic land savings. However, the country's dependence on non-EU land resources would effectively be eliminated

Approach 1 - Internal land use destination scenarios, Exports vs domestic consumption

The estimated domestic land savings across three export scenarios and two dietary transitions are here estimated. Based on literature averages, land-use reductions were −32% for the flexitarian/semi-vegetarian diet (Van Dooren and Aiking, 2015; Van Kernebeek et al., 2015; Van Dooren et al., 2014) and −44% for the vegan diet (Van Kernebeek et al., 2015; Van Dooren et al., 2014).

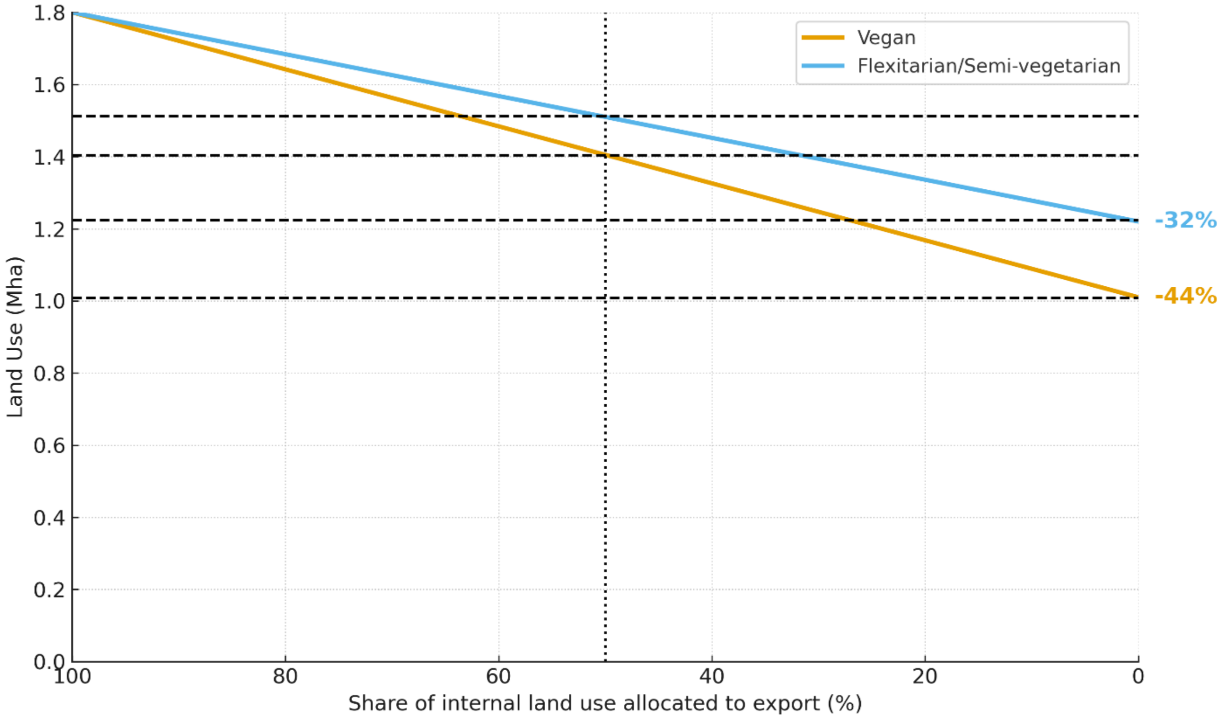

Figure 7 Estimated internal LU under dietary transition scenarios and varying export shares *Due to uncertainty regarding the extent to which domestic food demand drives internal LU in the Netherlands, three scenarios were developed that vary in the share of internal agricultural land allocated to exports. When all land is allocated to exports, no domestic land savings occur following dietary shifts. Conversely, when all internal land is used for domestic consumption, land-use reductions amount to −32% under the flexitarian/semi-vegetarian diet and −44% under the vegan diet.*

When 100% of internal LU is dedicated to exports, dietary change does not reduce domestic LU. Under a 50% export share, savings amount to 0.29 Mha (flexitarian) and 0.39 Mha (vegan). When all agricultural land serves domestic consumption, savings reach 0.58 and 0.79 Mha, respectively. After excluding peatland, afforestation-eligible areas range from 0.09 to 0.59 Mha (Table 5).

***Table 5 Estimated land saving [Mha] when shifting diet in the Netherlands varying the internal LU, and changing the share of internal LU destined to Export**. When all the land is used to produce exports crops, the change in diet does not have a strong effect on LU. When all the land is used for internal use, it is assumed that change in dietary requirement directly translates in LU change. The minus peatland column represents the land that would be dedicated to afforestation and in which the C sequestration is simulated.*

Land savings [Mha]	Vegan (-44%)		Vegetarian/flexitarian (-32%)	
	Total	Minus peatland (0.20 Mha)	Total	Minus peatland (0.20 Mha)
100 % for export	No land savings		No land savings	
50% for exports	0.39	0.19	0.29	0.09
0% for exports	0.79	0.59	0.58	0.38

Approach 2 - Reallocation under a Self-Sufficient EU Food System

In the second approach, the EU-27 is assumed to operate as a self-sufficient, net-zero import–export food system. The average land requirement for food under a diet with a 50% reduction in animal-source foods (ASF) was taken as 0.17 ha/person (Westhoek et al., 2014).

The total EU land requirement for food production was derived by multiplying this value by the EU-27 population (450 million people(European Union, n.d.), resulting in a total of 76.5 Mha. This area was divided equally into two allocation pools — one population-based and one area-based — each representing 50% of the total.

The Netherlands' share of land was then calculated based on its proportion of EU population and area. Detailed computational steps are presented in Appendix 2. The resulting national land allocation is summarised below:

- Population-based allocation: 1.53 Mha
- Area-based allocation: 0.31 Mha
- **Total allocated land: 1.84 Mha**

This value is nearly equivalent to the current Dutch agricultural LU of between 1.8Mha (Statistics Netherlands, 2025) indicating no net domestic land savings under this 50 % ASF reduction scenario. However, this configuration implies the full internalisation of production within Europe, effectively eliminating the Netherlands' reliance on land resources beyond the EU.

3.2 Carbon sequestration in afforestation

This section presents the outcomes of the afforestation simulations, which assessed C pools in the assumed systems. The model outputs the development of C stocks across three different pools: soil, biomass, and products. Section 3.2.1 introduces the eight simulated scenarios, which vary in forestry management, climatic projections, and the efficiency of wood product processing and recycling. Section 3.2.2 examines the temporal evolution of C stocks, comparing the accumulation patterns and long-term stability between the two forestry management types. Finally, Section 3.2.3 analyses the influence of product efficiency and climate projections on the final outcomes

3.2.1 Overview of scenario

The results indicate that the choice of forestry type/management exerts largest influence on C sequestration, while the effects of product efficiency and climatic projection are comparatively modest as visible in table 6.

Overall, the PB scenario sequesters more C than the NB scenario, reaching a total stock after 200 years of approximately 300 tC ha^{-1} compared to 189 tC ha^{-1}, respectively (Figure 8 and Figure 9).

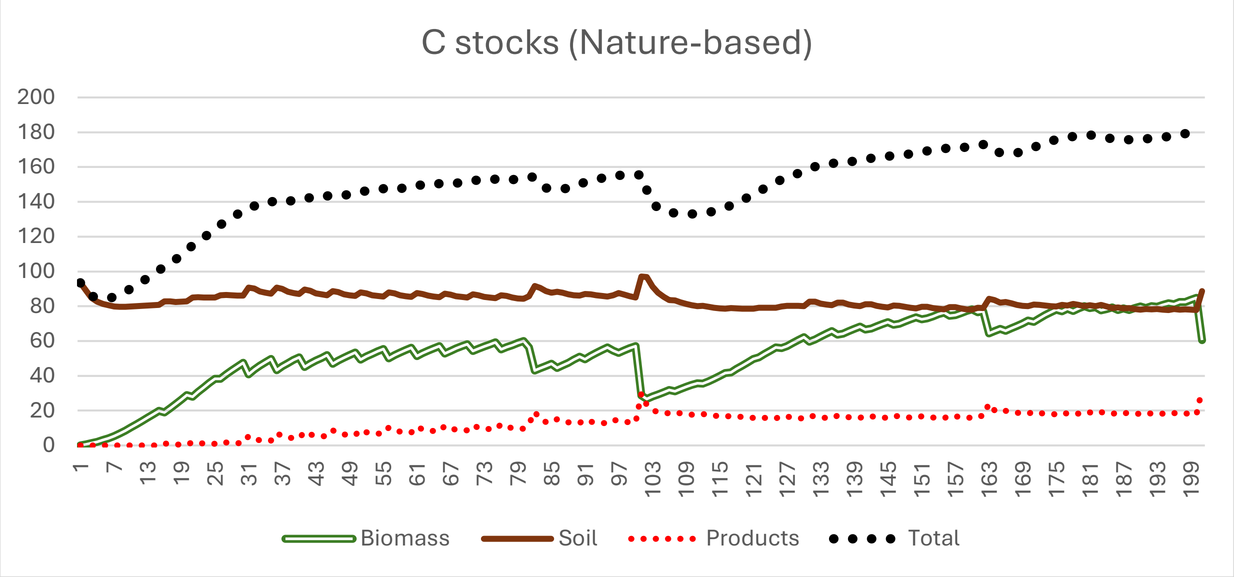

Figure 8 Development of C stocks (tC ha $^{-1}$) in the Nature-Based (NB) forestry system (Scots pine, oak, silver birch) under high product efficiency and the higher-end climate projection over 200 years

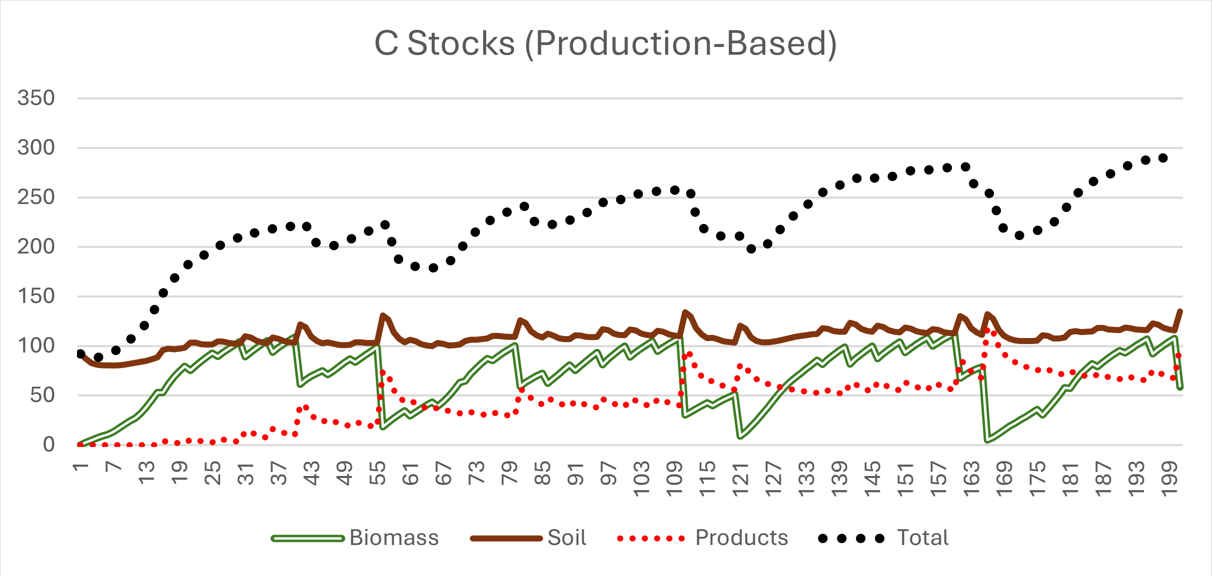

Figure 9 Development of C stocks (tC ha $^{-1}$) in the Production-Based (PB) forestry system (Douglas fir, Japanese larch) under high product efficiency and the higher-end climate projection over 200 years.

In the NB scenario, C stocks increase steadily during the first three decades, reaching approximately 140 tC ha^{-1}. After this initial phase, the rate of sequestration slows considerably, with the total stock peaking at around 180 tC ha^{-1} after 180 years. Soil C exhibits an initial sudden decline and subsequently remains relatively stable, and constitutes the larger C pool.

In contrast, the PB scenario, exhibits a faster and higher accumulation of C. After thirty years, total stocks already exceed 200 t C ha^{-1} and continue to rise throughout the simulation period. At 200 years, the PB system reaches a peak of 290 t C ha^{-1}. Projections suggest that sequestration would continue to increase in the long run, though it is expected to eventually stabilize. While biomass remains the dominant pool, soil and product pools contribute substantially, with the product pool displaying a steady upward trend. Overall, the PB scenario sequesters considerably more C than NB.

3.2.2 Influence of product efficiency and climate projections

Tables 6 presents the total C stocks at year 2050 and 2055 (assuming that the afforestation start in 2025) for the NB and PB scenarios. Each scenario comprises four sub-scenarios that vary according to following two dimensions:

At year 2155 (130 years after afforestation) In the NB system, total Cstocks range between 155 and 158 tC ha^{-1}, depending on product efficiency and climatic projection. In the PB system, the range is broader, from 226 to 335 tC ha^{-1}. The maximum observed difference, is about 10 tC ha^{-1}, occurs between two PB low product efficiency and lower climate projection and PB high product efficiency and higher climate projection.

Table 6 Total carbon stocks (tC ha $^{-1}$) in the Nature-Based (NB) and Production-Based (PB) forestry systems at two time horizons. *Stocks are shown at 25- and 130-year horizons. For each forestry system there are 8 scenarios combination of three dimensions: time horizon, climatic projections, and product processing and recycling efficiency.*

NB total C [tC ha^{-1}]	25 yr		130 yr	
Climatic projection →	Lower end	Higher end	Lower end	Higher end

Low product efficiency	126	127	156	159
High product efficiency	126	127	155	158
PB total C [tC ha^{-1}]				
Low product efficiency	200	201	226	228
High product efficiency	200	201	233	236

Across both forestry types, higher-end climate projections consistently result in slightly greater total C stocks than lower-end projections. This difference arises because the two climate projections vary in average temperature and summer water deficit: the higher-end scenario is warmer and drier. In the CO_2FIX model, climate parameters affect only the soil module. Higher temperatures accelerate organic matter decomposition, while increased water deficit slows it down. Therefore, the slightly higher C stocks under the higher-end scenario suggest that reduced soil moisture has a stronger effect in limiting decomposition than the temperature increase has in enhancing it—resulting in a net gain in soil C storage.

The effect of product efficiency is less straightforward. In the NB system, increasing product efficiency does not enhance total C sequestration, whereas in the PB system, higher product efficiency is associated with slightly greater total C stocks (table 6).

When expressed in CO_2 equivalents, total sequestration ranges from 127 to 398 t CO_2 eq ha^{-1} in the first 25 years, and from 238 to 509 t CO_2 eq ha^{-1} over the 130-year horizon. The corresponding annual average sequestration rates range from 5.1 to 15.9 t ha^{-1} yr^{-1} in the first 25 years, and from 1.8 to 3.9 t ha^{-1} yr^{-1} over 130 years (Table 7).

Table 7 Total and annual CO_2 sequestration 7uat 25- and 130-year horizons *in the Nature based scenario (Scots Pine, Birch, and oak) and in the Production based scenario (Scots Pine, Birch, and oak)*

	25 yr CO_2 sequestration		**130 yr CO_2 sequestration**	
	Total [t ha^{-1}]	**Annual [t ha^{-1} yr^{-1}]**	**Total [t ha^{-1}]**	**Annual [t ha^{-1} yr^{-1}]**
NB	127	5.1	238	1.8
PB	398	15.9	509	3.9

3.3 C sequestration trough afforestation in plant-based scenarios

In this section, the results from the previous sections are combined. Under *Approach 1* for estimating land savings, there are domestic land savings and therefore potential for C sequestration, whereas under *Approach 2* there are no internal Dutch land savings and thus no domestic sequestration.

For Approach 1, the land savings (in Mha) for each combination of dietary shift and trade assumption are multiplied by the C stocks (t C ha^{-1}) of each forestry scenario. Table 8 shows the total C that would be sequestered on well-drained freed-up land in the Netherlands when afforested. Two time horizons are considered: 2050 and 2155, representing 25 and 130 years of afforestation respectively (assuming a starting date of 2025).

Table 8 Total carbon sequestered (Mt C) by 25 at 25- and 130-year horizons under Approach 1, by dietary scenario and forestry system. *Calculations assume that afforestation begins in 2025 and prioritizes sparing 0.20 Mha of peatland before afforestation can occur. Land savings are calculated assuming either that changes in food demand directly drive land demand (0% exports) or that half of Dutch agricultural land is affected by changes in internal consumption (50% exports). NB refers to the Nature-Based forestry scenario, where native tree species are employed, whereas PB stands for the Production-Based forestry scenario, where fast-growing large tree species are used with intensive thinning management.*

Total CO_2 Sequestered [Mt CO_2]	Vegan		Flexitarian/Semi-vegetarian	
	50% Exports	0% Exports	50% Exports	0% Exports
NB – 25 yr	24	75	11	48
NB – 130 yr	45	140	21	90
PB – 25 yr	76	235	36	151
PB – 130 yr	97	300	46	193

The largest sequestration occurs after 130 years (in 2155), as forestry systems continue to accumulate C after 25 years. The PB forestry scenarios sequester more C than the NB ones. Moreover, in the 50% export scenarios there is less freed-up land and thus less sequestration than in the 0% export cases, because half of the agricultural land remains dedicated to export production and is therefore not affected by dietary shifts. The vegan transition frees up more land and therefore sequesters more C. In the 50% export scenarios, vegan land savings are roughly double those of the flexitarian/semi-vegetarian scenarios, whereas in the 0% export scenarios they are about 1.5 times greater

These data represent only the sequestration potential through afforestation of (non-peatland) land savings in the Netherlands. C that could be sequestered in freed-up peatland or in land savings abroad is beyond the scope of this analysis.

When expressed as annual CO_2-equivalent sequestration (table 9), the same general patterns persist: PB systems store more C than NB systems, and 0% export scenarios yield higher mitigation potential than 50% export ones due to greater afforestation area. However, Table 9 shows that annual sequestration rates decline over time, even though total C stocks continue to rise, as forests mature and C uptake slows

Table 9 Annual CO_2-equivalent mitigation potential (Mt CO_2 eq. yr^{-1}) for different combinations of dietary transition, trade assumption, and forestry system in the Netherlands. *Values are presented as annual averages for the first 25 and 130 years. The 50% exports scenario assumes that half of Dutch agricultural land is used for export and the other half for domestic consumption, whereas 0% exports means that all agricultural land serves domestic consumption. The Nature-Based (NB) forestry scenario employs native tree species, while the Production-Based (PB) scenario involves fast-growing large tree species and intensive thinning management.*

Annual CO_2 Sequestration [Mt CO_2 eq. yr^{-1}]	Vegan		Flexitarian/Semi-vegetarian	
	50% exports	0% Exports	50% exports	0% Exports
NB – 25 yr	0.97	3.00	0.46	1.93
PB – 25 yr	3.02	9.39	1.43	6.05

AVERAGE-25 yr	**2.00**	**6.20**	**0.95**	**3.99**
NB – 130 yr	0.35	1.08	0.16	0.70
PB – 130 yr	0.74	2.31	0.35	1.49
AVERAGE-130 yr	**0.55**	**1.70**	**0.26**	**1.09**

3. Discussion

This chapter is organized into six sections. Section 3.1 discusses the patterns, limitations, and novelty of the literature review on land requirements and land reductions. Section 3.2 addresses the estimation of land savings, comparing the results with previous studies and outlining their limitations. Section 3.3 presents the modelling of C stocks in afforestation through Climate-Smart Forestry (CSF), comparing outcomes with existing literature and identifying key limitations. Section 3.4 integrates land savings and sequestration rates to estimate the overall mitigation potential of dietary shifts, also in comparison with literature. Section 3.5 formulates methodological and policy recommendations for future research and implementation. Finally, section 3.6 discusses the broader relevance of these findings.

3.1 Land requirements review

The review of food land requirements (LR) in the Netherlands indicates that reductions in animal-source foods (ASF) are consistently associated with lower land requirements per person. Current Dutch dietary patterns result in a LR between 0.26 and 0.15 ha person^{-1}, while more plant-based diets such as the Mediterranean and vegetarian patterns require approximately 0.12–0.10 ha person^{-1}, with the vegan diet showing the lowest value at 0.08 ha person^{-1} (van Dooren et al., 2014). The finding that vegan diets are the least land-demanding is consistent with broader meta-analyses and systematic reviews (Aleksandrowicz et al., 2016; Hallström et al., 2015; Kalmpourtzidou et al., 2025).

When dietary changes are combined with circularity principles—such as using by-products and reducing waste—further reductions in LU can be achieved. Tamsma et al. (2025) estimated a LR of 0.05 ha person^{-1}, and van Kernebeek et al. (2016) reported a theoretical minimum of 0.04 ha person^{-1}. However, these estimates are based on optimization models that identify theoretical optima rather than predicting realistic LU under current or near-future conditions. Consequently, these results should be interpreted as potential rather than achievable land-use efficiencies.

A comparison of the Netherlands with other European countries and global averages confirms that lower ASF consumption consistently leads to lower LR. Interestingly, the results suggest that the larger the geographical scale, the higher the LR, even when diet composition is held constant. This may reflect differences in production efficiency across scales. For instance, the Dutch food system shows a relatively low baseline LR (0.15–0.26 ha person^{-1}), whereas global averages are substantially higher—approximately 0.56 ha person^{-1}, considering a total agricultural area of about 5 billion ha for 8 billion people in Röös et al. (2017). Given that about 68% of global agricultural land is used as permanent pasture (Röös et al., 2017) and that globally ASF consumption remains lower than in the Netherlands (Miller et al., 2022; Speedy, 2003), this implies that global pasture use is generally more extensive and less productive. In contrast, Dutch livestock and crop systems are highly intensified, producing more output per unit of land.

This review offers new insights into the trends and variability of land requirements across dietary patterns and spatial scales. Notably, a comprehensive systematic review quantifying LR per person by diet type has not yet been conducted, highlighting the novelty of this synthesis.

Nevertheless, the findings show substantial variation even within similar diet categories. For example, Dutch baseline values range between 0.26 and 0.15 ha person^{-1}, and the reasons for this variability are not fully clear. Differences in data sources, yield assumptions, and methodological choices likely contribute. Furthermore, the estimates by Belgacem et al. (2021)

appear considerably higher than other studies for the same diet type—reporting, for example, 0.53 ha person^{-1} for a Mediterranean diet, while other studies estimate values between 0.10 and 0.16 ha person^{-1}. The cause of this discrepancy remains uncertain. Belgacem et al. (2021) used the life cycle assessment (LCA) dataset from Poore and Nemecek (2018), which applies a cradle-to-retail system boundary, including LU associated with processing, packaging, transport, and waste. This might suggest an overestimation relative to studies with cradle-to-farm-gate boundaries, such as Westhoek et al. (2014). However, since the reviewed studies applied a range of LCA boundaries—from cradle-to-farm-gate to cradle-to-grave—the system boundary alone seems to have only a minor effect on LR estimates.

Overall, reducing ASF in Dutch diets could halve the per-capita land requirement, with potential for further reductions under circular practices.

3.2 Land savings In the Netherlands

This thesis employed alternative approaches to calculate land savings, explicitly considering the uncertainty arising from the strong trade orientation of the Dutch food system. It is unlikely that dietary changes within the Netherlands would directly drive large domestic reductions in LU, as trade and market dynamics act as buffers between consumption and production.

Approach 1 simulated three scenarios: in the first, all domestic agricultural production is exported; in the second, 50% of Dutch production is consumed domestically; and in the third, all agricultural production is used for domestic consumption (0% export). It was assumed that changes in dietary land demand directly influence LU reduction only in the share of land used for domestic consumption, while export-oriented land remains unaffected. Under the first scenario (100% export), no land savings occur. In the second (50% export), land savings amount to 0.29 and 0.39 Mha for flexitarian/semivegetarian and vegan diets, respectively. In the third scenario (0% export), land savings reach 0.58 and 0.79 Mha for the same diets. Considering that the total agricultural area in the Netherlands is about 1.8 Mha (Statistics Netherlands, 2025), these values represent approximately 16–44% of the national agricultural area, depending on the scenario.

These estimations are novel because previous studies estimating the LU reduction potential of dietary shifts in the Netherlands have mainly relied on life cycle assessment (LCA) approaches. LCA-based analyses calculate the overall reduction in LU, encompassing both domestic and imported land. Van Dooren et al. (2014) reported a 42% reduction for semivegetarian, 53% for vegetarian, and 58% for vegan diets, while Dooren and Aiking (2015) found a 32% reduction for flexitarian diets.

In contrast, Tamsma et al. (2025), van Selm et al. (2025), and Van Kernebeek et al. (2015) explored LU in scenarios where the Netherlands sources all food locally within a circular food system and reduces the consumption of animal-sourced foods (ASF). Their results indicate potential land savings of 1.1 Mha and 1.3 Mha, respectively. Although these studies demonstrate the considerable potential of circular food systems, their scenarios involve utter changes, relying on optimisation models that minimise LU under stringent constraints leading to a very low number. Moreover, they do not reflect the current structure of the Dutch food system, where roughly 80% of food produced is exported and around 75% of supermarket food is imported (Strootman Landschapsarchitecten & Centre for Environmental Sciences Leiden University, 2024 Additionally, both Tamsma et al. (2025) and Van Kernebeek et al. (2015) assume relatively low energy intakes compared with present Dutch dietary patterns, further contributing to the underestimation of potential land savings.

Another limitation of this thesis is the exclusion of pets. According to RIVM (2022), there are approximately 2 million dogs, 3 million cats, and numerous other pets in the Netherlands. Because the literature used for land-requirement estimates did not account for pets, they were also excluded from this analysis. However, since pets consume ASF residues, their omission likely leads to an overestimation of the calculated land savings.

A further limitation is that this approach considers only domestic land savings, without accounting for the reduction of imported land. Imported land also offers potential for afforestation and C sequestration; therefore, this omission likely leads to an underestimation of the total sequestration potential. Moreover, freeing up Dutch agricultural land may not represent the optimal spatial strategy for afforestation, as regions with lower agricultural productivity but higher C sequestration potential might offer greater overall benefits, as discussed by Hayek et al. (2024).

Given that this estimation involves numerous assumptions and variables, a second approach was applied to complement and cross-check the results.

Approach 2 assumes that the EU-27 functions as a self-sufficient food system. It employs LU data from Westhoek et al. (2014), who estimated a land requirement of 0.17 hectares per person under a diet with 50% less meat consumption. The total land required to sustain the EU-27 population was then allocated to each member state proportionally to its population and land area. This approach indicates that the total land required to meet Dutch food demand would be 1.84 Mha, which is nearly equivalent to the current national LU. This suggests that no internal Dutch land savings would occur. However, under this EU-wide self-sufficiency scenario, there would likely be a reduction in virtual land imports from outside Europe. It should also be noted that this scenario represents a milder dietary shift compared with the semivegetarian/flexitarian and vegan diets considered previously. The main limitation of this approach lies in its reliance on a single source for land-requirement data, which constrains its robustness and reliability.

3.3 Afforestation’s C stocks modelling

The net CO_2 sequestration estimated by this thesis averages 5.1 t CO_2 ha^{-1} yr^{-1} in the NB scenario and 15.9 t CO_2 ha^{-1} yr^{-1} in the PB scenario over the first 25 years. Over 130 years, mean annual rates decline to 1.8 t CO_2 ha^{-1} yr^{-1} (NB) and 3.9 t CO_2 ha^{-1} yr^{-1} (PB).). The different combinations of climate projections and product efficiency scenarios show little variation among each other; therefore, they were clustered into the two groups NB and PB.

Research focused specifically on Climate-Smart Forestry (CSF) sequestration potential in the Netherlands is limited; however, available studies on afforestation provide relevant benchmarks. Boosten et al. (2022) report that new forests in the Netherlands can sequester 3–15 t CO_2 ha^{-1} yr^{-1} during the first 10 years, while values cited via Roest et al. (2025) indicate mean rates for mixed forests of 2.4 t CO_2 ha^{-1} yr^{-1} on poor sands, 7.9 t CO_2 ha^{-1} yr^{-1} on rich sands, and 13 t CO_2 ha^{-1} yr^{-1} on clay soils in the first decade. Grafton et al. (2021) estimate above-ground sequestration in planted oak of 10–16.9 t CO_2 ha^{-1} yr^{-1}, noting their scope is limited to above-ground biomass. Arets *et al.* (2020) report approximately 13.3 t CO_2 ha^{-1} yr^{-1} over 30 years under sustainable management on mineral soils. Although most literature reports 10-year averages whereas this thesis reports 25-year averages. Early-decade rates may be lower due to initial soil C losses and because stand growth typically peaks between roughly 15 and 35 years, which can elevate 25-year means relative to 10-year means.

Beyond corroborating short-term rates, this thesis extends the comparison to longer horizons (25 and 130 years), which is relevant because durable climate benefits depend on long term persistence of C stocks. The CSF framing is operationalized using two bookend scenarios: NB (nature-based, native species, longer rotations) and PB (production-based, fast-growing species, heavier thinnings, shorter rotations). The intended interpretation is that real-world CSF systems will fall between these bounds; this is a simplifying assumption, as actual practices vary.

Several limitations qualify the estimates. First, the allocation of harvested material among logwood, pulp and paper, and slash was derived via coarse, rule-based factors. These factors were constructed by combining literature thresholds for minimum stem diameters (e.g., excluding stems <10 cm from logwood), age-specific diameters from yield tables, leading to rough age- and cohort-specific allocations. Second, default product-processing and recycling efficiency parameters originate from the European forest sector in 2002. The “high-efficiency” and “low-efficiency” parameterizations produced very similar outcomes, and in some cases the nominally higher-efficiency setting yielded lower sequestration, suggesting these parameters are outdated and not discriminative for current conditions. Third, yields for mixed-species stands were approximated as the weighted sum of monoculture yields. By ignoring interspecific interactions, this approach may underestimate productivity and C uptake where positive complementarity (e.g., niche partitioning, facilitation) occurs. Fourth, the representation of climate change only in the soil module likely introduced spurious effects in the climate comparison. In CO2FIX, biomass growth is driven by fixed yield tables derived under historical climate conditions, meaning that tree growth does not respond to warming or increased summer drought. Under the high-end climate projection, reduced soil moisture slows decomposition in the Yasso module, resulting in slightly higher soil carbon stocks than in the milder scenario. However, this outcome likely reflects a modelling artefact rather than a plausible ecological response, because the model does not capture the negative impacts of higher temperatures and summer rainfall deficit on tree growth. Evidence for the Netherlands indicates that warming and increased summer drought are expected to reduce the vitality and growth of several temperate tree species (Bouwman, 2025). Consequently, total carbon stocks under a warmer, drier climate are likely overestimated in this study.

Despite these limitations, model outputs align with the range of values reported for afforestation in the Netherlands and are appropriate for the thesis’s broader aim of estimating sequestration on spared land. A major remaining limitation is the exclusion of bioenergy substitution effects. Omitting energy use of harvested wood likely understates total mitigation, because displacement of fossil fuels can dominate long-run system benefits in forest C accounting frameworks; afforestation and energy substitution case studies frequently show substitution benefits becoming the largest component at multi-century scales (Forster et al., 2021; Kaul, Moheren & Dadhwal, 2010). Incorporating such pathways would be necessary to fully assess CSF’s mitigation potential.

3.4 CO_2 sequestration potential of dietary shifts

This thesis aimed to estimate the potential C sequestration through Climate Smart Forestry (CSF) on well-drained freed-up land under different dietary shift scenarios. The total area available for afforestation was calculated as the freed-up agricultural land minus 0.20 Mha of agricultural peatland.

The results show that the sequestration potential in the first 25 years ranges from 1.12 Mt CO_2 eq. yr^{-1} in the 50% export, Nature-Based (NB) forestry, flexitarian/semi-vegetarian scenario to 19.85 Mt CO_2 eq. yr^{-1} in the 0% export, Production-Based (PB) forestry, vegan scenario. Over the 130-year time horizon, the range decreases to between 0.81 Mt CO_2 eq. yr^{-1} in the 50% export, NB forestry, flexitarian/semi-vegetarian diet and 9.76 Mt CO_2 eq. yr^{-1} in the 0% export, PB forestry, vegan diet. On average, the annual sequestration potential amounts to 3.28 Mt CO_2 eq. yr^{-1} during the first 25 years and 0.89 Mt CO_2 eq. yr^{-1} over the 130-year horizon.

To put these results in context, the Dutch food system emitted approximately 52 Mt CO_2 eq. yr^{-1} in 2018, accounting for about 31% of total national emissions (Crippa et al., 2021). The findings of this thesis therefore suggest that afforestation of the freed-up land could sequester about 6% of current annual food system emissions in the first 25 years and about 1.7 % in the 130-year time horizon.

When compared with the literature, there are no Dutch-specific studies, but some contextual comparisons can be drawn from global and regional analyses. Hayek et al. (2021) used a global modelling approach to estimate the C sequestration potential resulting from dietary transitions to the Planetary Health Diet (PHD) and a vegan diet. They found that the land spared through these transitions could enable natural ecosystem restoration, leading to cumulative sequestration between 6.4 and 9.1 Gt CO_2 yr^{-1} for the PHD transition and 10.9 to 15.44 Gt CO_2 yr^{-1} for the vegan transition by 2050, corresponding to mitigation of 48% and 82% of total global food system emissions, respectively.

These figures are clearly higher than the relative reductions estimated in this thesis compared to total Dutch food system emissions. Several factors may explain this difference. First, this thesis simulated afforestation only on domestic freed-up land, while dietary shifts would also reduce demand for imported agricultural land. Second, this study excluded freed-up peatlands, which offer considerable additional mitigation potential. Third, the Netherlands may have a relatively low C opportunity intensity: its productive agricultural land is already highly efficient, meaning that shifting away from Dutch feed and pasture production may yield less additional C sequestration compared to less productive livestock regions.

Similarly, Kozicka et al. (2023) modelled a scenario in which 50% of animal-source foods (ASF) are replaced by plant-based alternatives by 2050. They found that deforestation would be halted and 12% of global agricultural land could be freed for afforestation—equivalent to about 1.5 Gt CO_2 yr^{-1} between 2020 and 2025, or roughly 9.3% of total food system emissions (Crippa et al., 2021; Poore & Nemecek, 2018). These findings are broadly consistent with those of this study, although Kozicka et al. (2023) considered a milder dietary transition and a much shorter time frame of five years.

Jones et al. (2023) found that, in Wales (UK), dietary shifts toward healthier, more plant-based diets combined with reduced food waste could release approximately 0.32–0.39 Mha of agricultural land by 2050, enabling extensive afforestation and peatland restoration. These actions could turn the land-use sector into a net C sink of about 3 Mt CO_2 eq. yr^{-1}, which, according to the Welsh Government (2025), corresponds to 58% of total agricultural emissions. Although this figure is lower in absolute terms than the Dutch potential estimated in this thesis, it is comparable when considering the smaller size of Wales—roughly half the area and one-sixth the population of the Netherlands. The mitigation relative to national food emissions, however, is higher in Wales, as their study considered only agricultural emissions, excluding processing, transport, and food waste, as well as imported food. Overall, the findings are consistent in direction and magnitude.

Likewise, Harwatt and Hayek (2019) estimated that reforesting land currently used for UK animal agriculture could sequester 149 Mt CO_2 yr^{-1} while still providing sufficient calories and proteins for the population. This figure corresponds to approximately 150% of annual UK agricultural emissions (47.7 Mt CO_2 eq.; Department for Environment, Food & Rural Affairs, 2025). The mitigation potential estimated is much higher than that found in this thesis, mainly because the proposed measure is considerably more extensive, sparing about 11.6 Mha of pasture and feed cropland—around 70% of total UK agricultural land. The authors claim that the remaining 6 Mha of agricultural land could still feed the 69 million UK citizens, implying a land requirement of approximately 0.09 ha per person, which may be optimistic to achieve through dietary shifts alone. Therefore, the results of Harwatt and Hayek (2019) likely overestimate the practical potential compared to the findings of this study.

As for the limitations, merging the results was relatively straightforward. The main limitations arise from the two components of the analysis: the estimation of land savings from dietary shifts and the calculation of afforestation sequestration potential. This study focused exclusively on potential sequestration through afforestation on well-drained soils. Another key limitation is the consideration of afforestation only within domestic land savings, overlooking the potential sequestration in virtual imported land outside the Netherlands, that is no longer needed to feed the Dutch populations. A last limitation is the exclusion of the bioenergy module in the CO2fix model; accounting for the energy substitution given by the harvested timber would increase the estimated mitigation potential, especially in the long term when the stand will reach the maximum biomass (Forster et al., 2021; Kaul, Moheren & Dadhwal, 2010). Moreover, the, dietary shifts reduce greenhouse gas emissions not only through land-use change but also directly by lowering enteric methane, manure-related emissions, and upstream feed production.

Three rough estimates illustrate the broader mitigation potential associated with Dutch dietary shifts:

- Drained peatlands emit between 20 and 29 t CO_2-eq ha^{-1} yr^{-1} (IPCC, 2014; Greifswald Mire Centre, 2016). Rewetting the 0.20 Mha of agricultural peatland in the Netherlands could therefore mitigate an additional 4.9 Mt CO_2-eq yr^{-1}. This value is comparable to the average sequestration rates of 7 Mt CO_2-eq yr^{-1} in the first 25 years and 3.9 Mt CO_2-eq yr^{-1} over 130 years estimated for afforestation in this thesis.
- Considering that (i) approximately 65% of livestock-related emissions stem from non–land-use-change processes (FAO, 2006), (ii) the average Dutch diet emits about 1.4 t CO_2-eq yr^{-1} $person^{-1}$ (Temme et al., 2014), and (iii) shifts to vegetarian or vegan diets reduce dietary emissions by 23–53% (Aleksandrowicz et al., 2016), a complete national transition—assuming a population of 18 million—would reduce diet-related emissions by approximately 5.8–13.4 Mt CO_2-eq yr^{-1}. Considering only non–land-use-change emissions and applying the global 65% share to the Dutch context, the reduction would be roughly 3.8–8.7 Mt CO_2-eq yr^{-1}.
- Considering that (i) the Netherlands imports approximately 3.5 million hectares of cropland and pasture, (ii) dietary shifts in this thesis reduce land demand by 32% (flexitarian) to 44% (vegan), and (iii) the average carbon sequestration rate in the

European Union is about 10 t CO_2-eq ha^{-1} yr^{-1} (Bernal et al., 2018)—a conservative value, since some sequestration would likely occur in higher-uptake subtropical and tropical regions—the sequestration potential on spared imported land is estimated to range between 11.2 Mt CO_2-eq yr^{-1} (flexitarian diet) and 15.4 Mt CO_2-eq yr^{-1} (vegan diet).

Combined (excluding bioenergy substitution), these effects add ~19.9–28 Mt CO_2-eq yr^{-1}, corresponding to 38–54% of Dutch food-system emissions (52 Mt CO_2-eq yr^{-1}; Crippa et al., 2021).

3.5 Recommendation

This study identifies several methodological and empirical gaps that warrant further research. Regarding the modelling of afforestation sequestration:(1) Future studies would benefit from the development of Dutch-specific yield tables that include mixed-species forestry systems and explicitly account for climate change effects on growth rates. The yield data used in this thesis relied on static, single-species tables that do not capture how growth may change due to potential interspecific interactions or shifting climatic conditions.
(2) The allocation of harvested material among logwood, pulp and paper, and slash should be refined through empirical validation, as the rule-based approach applied here introduces structural uncertainty.
(3) Context-specific data on product processing and recycling efficiency—reflecting Dutch forest sector conditions in 2025 and beyond—would improve model reliability.
(4) It would also be valuable to compare the outcomes from the CO2FIX model with those from other dynamic C accounting models to assess consistency and model sensitivity.
(5) Finally, future modelling efforts should incorporate the bioenergy substitution pathway to more comprehensively estimate the mitigation potential of Climate-Smart Forestry (CSF) systems. Excluding the energy substitution effect underestimates the total long-term mitigation potential, as the energy use of harvested wood can represent a major component of total system mitigation.

As for estimating freed-up land under dietary shifts:

(1) In the literature review on land requirements and reductions, studies were not clustered according to their methodological frameworks—particularly regarding LCA system boundaries (e.g., cradle-to-farm-gate vs. cradle-to-retail). Future research should account for these differences to improve comparability and identify discrepancies across studies.
(2) Integrating an economic partial equilibrium model, such as CAPRI, could enhance realism. Such a model can capture the interplay between demand, production, trade, and LU. The strong trade orientation of the Dutch agri-food sector limits the direct correspondence between domestic consumption changes and domestic LU; therefore, models that include market feedback mechanisms would better represent actual land-sparing outcomes.
(3) The widespread exclusion of pet food consumption in dietary land-use studies leads to systematic overestimations of available land. Given that pets consume a substantial share of animal-source foods, future analyses should quantify the land and emission implications of pet ownership at the national scale.

At the policy level, given the urgency of climate change, this study supports promoting dietary patterns with reduced animal-source food consumption to free up land for afforestation and ecosystem restoration. Where feasible, well-drained agricultural land in the Netherlands should be prioritized for afforestation under CSF management that balances C sequestration, biodiversity, and economic objectives. Integrating such measures into national and EU climate strategies could help align food, land, and climate policies toward achieving long-term C neutrality.

3.6 Relevance

This thesis bridges food system analysis and C sequestration modelling, linking dietary land requirements with afforestation potential. By integrating these two perspectives, it quantifies how dietary transitions toward plant-based patterns can free land for Climate-Smart Forestry and contribute to emission reduction targets. The findings highlight diet as a key driver of LU and C mitigation. The study provides evidence relevant to Dutch climate policies, such as the National Climate Agreement, the National Climate Act, and EU climate frameworks, by illustrating the potential of combined dietary and land-based strategies for achieving C neutrality.

4. Conclusion

This thesis assessed how dietary transitions toward plant-based patterns in the Netherlands affect land requirements and how much CO_2 could be sequestered if well-drained spared land were afforested under Climate-Smart Forestry. The analysis combined a systematic review of land requirements, a trade-sensitive estimation of domestic land savings, and dynamic carbon modelling.

Shifting from current Dutch diets to flexitarian, vegetarian, or vegan patterns substantially reduces land requirements. Under the 50% export scenario, dietary change frees 0.29 Mha (flexitarian/semi-vegetarian) to 0.39 Mha (vegan). Under the 0% export scenario, savings increase to 0.58–0.79 Mha, equivalent to 16–44% of total agricultural land. Approximately 0.20 Mha of this is peatland, assumed unsuitable for afforestation and therefore allocated to rewetting.

Afforestation of the remaining well-drained land can sequester 5–16 t CO_2 ha^{-1} yr^{-1} depending on management. At the national scale, this corresponds to 1.12–19.85 Mt CO_2-eq yr^{-1} by 25 years after afforestation and 0.81–9.76 Mt CO_2-eq yr^{-1} by 130 years after afforestation. Relative to contemporary Dutch food-system emissions (52 Mt CO_2-eq yr^{-1}), this represents 6% mitigation over 25 years and 1.7% over 130 years. Thus, dietary transitions combined with domestic afforestation offer a small contribution to food-system decarbonisation.

When additional effects—peatland rewetting, reduced livestock emissions, and afforestation on spared imported land—are included, the total mitigation potential of flexitarian and vegan diets rises to approximately 30 Mt CO_2-eq yr^{-1}, equivalent to 58% of Dutch food-system emissions

Methodologically, the thesis offers novel insights by linking a systematic review of dietary land-use requirements with an explicit treatment of trade-related uncertainty in domestic land savings and by integrating these outputs with dynamic CSF carbon accounting using CO2FIX for the Dutch context. Overall, the results show that afforestation on spared mineral soils provides only a small share of the mitigation needed to reduce Dutch food-system emissions, while the broader mitigation potential of such dietary shifts may be substantially larger. Although other measures may deliver larger emission reductions than the afforestation options assessed in this thesis, these measures are not mutually exclusive. Given the urgency of climate change, afforestation on freed-up mineral soils should be considered as one component within a broader portfolio of mitigation strategies enabled by dietary change.

Declaration of Generative AI

I hereby declare that I used ChatGPT for reviewing and proofreading, NoteBookLM for the initial screening of some of the consulted papers, and occasionally Consensus and Perplexity for literature queries. After using these tools, I have reviewed and edited the content as needed and I take full responsibility for the final content of this thesis.

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Appendices

Appendix 1

Table 1. characterisation of the studies considered (studies showing land requirements)

Study	Study area	Diets	Land requirements (ha person^{-1})	Underlying assumptions	Method
van Kernebeek et al., 2015	Netherlands	Grain (wheat), roots and tubers (potato, sugar beet), oil crops (rapeseed), legumes (brown bean), animal protein from ruminants (milk and meat), pork meat. AP (animal protein / total protein) ratio from 0% to 80%.	0% AP: 0.046; 12% AP: 0.040; 40% AP: 0.052; 50% AP: 0.056; 60% AP: 0.066 (to feed 15 million people)	Diet simulated with 2000 kcal person^{-1} and 57 g protein person^{-1}. No import/export of feed or food. Losses accounted for; 21% of total food crop losses could potentially be fed to animals.	Linear programming optimization model minimizing land use while meeting nutritional requirements at different AP levels. Based on Dutch average crop yields.
Tamsma et al., 2025	Netherlands	Recommended Voedingscentrum diet. (Dutch Nutrition Centre)	0.05	No import or export of feed and food. Circular food system.	Iterative linear optimization model (FOODSOM) with the objective of minimizing land use.
Van Selm et al. (2025)	Netherlands	Recommended modified to optimise either LU or GHG emissions. Hence Reduction in ASF especially beef.	Circular GHG optimisation 0.07 Circular LU optimisation 0.06	Circular food system Calories intake assumed to be between 2000 and 2500 kcal	Iterative linear optimization model (FOODSOM)
Dooren et al., 2014	Netherlands	Current, recommended, semi-vegetarian (50:50), vegetarian, vegan, Mediterranean.	Current: 0.19; Recommended: 0.12; Semi-veg: 0.11; Vegetarian: 0.09; Vegan:	All scenarios assume 2000 kcal person^{-1} (female adult). Food	Land footprint estimated via LCA (Agri-footprint 2.0).

			0.08; Mediterranean: 0.10.	quantities derived from literature.	
Alves et al., 2024	Netherlands (one of 10 countries)	Current, pooled cross-sectional dietary records (2010–2018).	Baseline: 0.26 ha person^{-1} year^{-1}.	Dietary records from EFSA European food database.	LCA approach; land-use values extracted from SHARP Indicator database.
Dooren & Aiking, 2016	Netherlands	Dutch consumption (CBS 2013), Mediterranean, guidelines-optimized (health and environment).	Dutch: 0.15; Mediterranean: 0.12; Guidelines: 0.11; Optimized: 0.10.	All diets assume 2500 kcal person^{-1}. Current and Mediterranean diets from literature; optimized diet based on linear programming.	LCA approach (Agri-footprint method).
Belgacem et al., 2021	Europe	European average diet, Western diet, Mediterranean diet.	European: 0.90; Mediterranean: 0.53; Western: 1.19.	All diets assume 2000 kcal person^{-1}. Dietary composition from FAO food balance sheets; footprints from Poore & Nemecek (2018).	Comparative LCA assessment.
Westhoek et al., 2014	European Union	Current diet (2007) vs. 25–50% replacement of animal-derived foods with plant-based foods.	Current: 0.23; Half ASF: 0.17 (−23% reduction).	Diet defined based on commodity supply. Assumes a proportional reduction in EU livestock production with ASF consumption reduction.	CAPRI model to estimate land use consequences of halving ASF.
Röös et al., 2017	Global	100% plant-based diet combined with either projected or healthy diets; four scenarios combining current yield/waste and 50% yield-gap closure / 50% waste reduction.	Current cropland + pasture: 0.625; Plant-based (both projected and healthy): 0.25; Plant-based with yield-gap and waste reduction: 0.125.	Average consumption 2500 kcal (healthy) or 2585–3131 kcal (projected). Protein 51–76 g person^{-1} day^{-1}. Meat replaced by pulses and cereals. Population increase considered to 2050.	Alternative diets constructed through substitution of meat and animal products. Regionalized global biomass flow model in Excel using FAO data.

Riera et al., 2025	Spain	EAT-Lancet Planetary Health Diet (PHD), Mediterranean diet.	PHD: 0.18; Mediterranean: 0.16 (both based on ~2198 kcal).	Data from Spanish ENRICA surveys; footprints from SHARP-ID database.	LCA approach using SHARP-ID database.
Bunge et al., 2024	Sweden	Combination of flexitarian, vegetarian, vegan diets with plant-based alternatives (PBA) or whole foods.	BAU: 0.26; Flexitarian: 0.20 (−24%); Vegetarian (PBA): 0.18 (−30%); Vegetarian (whole): 0.19 (−27%); Vegan (whole): 0.17 (−25%); Vegan (PBA): 0.15 (−42%).	Dietary scenarios built by replacing foods from baseline while keeping energy constant.	LCA using databases and food replacement modeling.
Lauk et al., 2022	Vienna (Austria)	Baseline, ÖGE (Austrian Nutrition Society) recommendations, EAT-Lancet, vegetarian, vegan.	Baseline: 0.35; ÖGE: 0.27 (−20%); EAT-Lancet: 0.23 (−26%); Vegetarian: 0.20 (−44%); Vegan: 0.17 (−53%).	Baseline intake 3117 kcal; modeled diets 2614 kcal; protein 67–99 g person^{-1} day^{-1}. Assumes Viennese consumption mirrors national average.	Land area calculated from 2014–2016 country-specific yields. FoodClim model used for footprint estimation.
Röös et al., 2018	Sweden	Current vs. 50% meat reduction (substitution with legumes).	Current: 0.34; Half-meat: 0.26 (−20–23%; 21,500 ha freed).	Substitution based on weight, not energy or protein. Prioritizes reduction in imported meat to increase domestic production.	Baseline from Statistics Sweden; LCA based on databases.

Table 2. characterisation of the studies considered (studies showing only land use reduction)

Study	Study area	Diets	Land-use reduction	Assumptions	Method
Simon et al., 2024 (Ch.3)	Europe (28)	EAT-Lancet diet with recommended protein intake (46 g person^{-1}) vs. current (82 g person^{-1}).	Circularity practices alone: −44%; with dietary shift: −60%.	Kcal not specified. Circularity practices include recycling of biomass and residues.	CiFoS biophysical food system optimization model.

		Shift from 60:40 to 40:60 AP:PBP ratio and adoption of circularity practices.			
Daas et al., 2025	Europe	“Plant-forward” dietary patterns averaging 52% AP.	−25%.	Not specific diets but clustered consumption patterns based on similarity.	EFSA food surveys linked with SHARP-ID database.
Chen et al., 2022	Europe and Central Asia (EUCA)	Current vs. EAT-Lancet Planetary Health Diet.	−15%.	Literature review of regional dietary transitions.	Review-based synthesis.
Aleksandrowicz et al., 2016	Global	Vegan, vegetarian, pescatarian, and partially plant-based diets (replacing meat/dairy).	−13% to −80% (m^2 $person^{-1}$ $year^{-1}$).	Review of multiple studies quantifying relative land-use differences.	Global systematic review.
Philippidis et al., 2021	Global	EAT-Lancet reference PHD vs. projected 2050 BAU diets.	−8% by 2050 relative to projected BAU.	Population growth increases baseline LU; PHD mitigates this increase.	MAGNET simulation model (Modular Applied General Equilibrium Tool).
Simon et al., 2024 (Ch.5)	Global	EAT-Lancet PHD optimized for land or GHG.	Land optimization: −91%; GHG optimization: −50%.	Complete circular food system including full biomass recycling and nutrient optimization. Baseline agricultural land: 36 million km^2.	CiFoS biophysical food system optimization model constrained by EAT-Lancet reference ranges and nutritional adequacy.
Balan & Trașca, 2024	Romania	Substitution of animal-based protein (ABP) with	100% substitution: −9% (714 m^2 per capita; 1,067,443 ha	Assumes domestic closed system where ABP replacement directly	LCA-based analysis using Romanian productivity data.

		plant-based protein (PBP) from 50% to 100%.	total reduction); 50% substitution: −3% (223 m^2 per capita).	reduces national land use.	
Prag & Henriksen, 2020	Denmark	EAT-Lancet Planetary Health Diet (PHD) implemented at 0–100% levels; soy partially replaced by local legumes.	50% PHD: −20%; 100% PHD: −46%.	PH diet contains 2500 kcal; assumes global implementation with constant yields and efficiencies.	Productivity and yield-based modeling grounded in Danish National Inventory Report.
Helander et al., 2021	Global supply chain of German food consumption	Current vs. sustainable and low-dairy vegetarian diets.	Sustainable diet: −43% cropland; Low-dairy vegetarian: −48%.	Energy intake fixed at 2796 kcal; fixed food waste trends and 2013 supply chain.	Footprint assessed using FABIO (environmental multi-regional input–output model).

Appendix 2 Calculations details for land savings

Approach 2 — Reallocation under a Self-Sufficient EU Food System

This section outlines the calculation steps for estimating the Netherlands' land allocation under a self-sufficient European food system, assuming net-zero food imports and exports.

1 Total EU land requirement under the alternative diet

$$
\begin{aligned}
LU_{\text{EU,total}} &= LU_{\text{pc}} \times P_{\text{EU}} \\
LU_{\text{EU,total}} &= 0.17 \text{ ha/person} \times 450{,}000{,}000 \text{ people} = 76.5 \text{ Mha}
\end{aligned}
$$

Data source: Westhoek et al. (2014): A reduction of 50% in ASF in Europe would lead to a land requirement of 0.17 ha person^{-1}

2 Division of total EU land into allocation pools

The total land requirement was divided equally between population-based and area-based allocations:

$$
LU_{\text{EU,pop}} = LU_{\text{EU,area}} = \frac{LU_{\text{EU,total}}}{2} = 38.25 \text{ Mha}
$$

3 Population-based allocation for the Netherlands

$$
\begin{aligned}
LU_{\text{NL,pop}} &= \frac{LU_{\text{EU,pop}}}{P_{\text{EU}}} \times P_{\text{NL}} \\
LU_{\text{NL,pop}} &= \frac{38.25}{450} \times 18 = 1.53 \text{ Mha}
\end{aligned}
$$

4 Area-based allocation for the Netherlands

$$
\begin{aligned}
LU_{\text{NL,area}} &= \frac{LU_{\text{EU,area}}}{A_{\text{EU}}} \times A_{\text{NL}} \\
LU_{\text{NL,area}} &= \frac{38.25}{410} \times 3.3 = 0.31 \text{ Mha}
\end{aligned}
$$

5 Total allocated land for the Netherlands

$$
\begin{aligned}
LU_{\text{NL,total}} &= LU_{\text{NL,pop}} + LU_{\text{NL,area}} \\
LU_{\text{NL,total}} &= 1.53 + 0.31 = 1.84 \text{ Mha}
\end{aligned}
$$

This total (1.84 Mha) closely matches the current Dutch agricultural land use of2 Mha (CBS, 2025;CBS 2022), confirming the absence of net domestic land savings in this self-sufficient EU scenario.

Appendix 3 Soil module details, equations, and parameters

Litter inputs (u_i) from each biomass component are grouped into:

- Non-woody litter (NWL): foliage and fine roots
- Fine-woody litter (FWL): branches and coarse roots
- Coarse-woody litter (CWL): stems and stumps

NB Roots are separated into fine/coarse using the branch-to-foliage ratio.
Litter entering soil is distributed into three chemical fractions:

- Extractives (EXT)
- Celluloses (CEL)
- Lignin-like compounds (LIG)

and subsequently into:

- Humus 1 (HUM1)
- Humus 2 (HUM2)

Each compartment j decomposes at rate k_j and transfers a fixed fraction p_j to the next, more stable pool.
The pool dynamics follow first-order equations:

$$\frac{d\,FWL}{d\,t} = (uFWL) - (kFWL \cdot FWL)$$

$$\frac{d\,CWL}{d\,t} = (uCWL) - (kCWL \cdot CWL)$$

$$\frac{d\,EXT}{d\,t} = (uNWL \cdot cNWL, EXT) + (kFWL \cdot FWL \cdot cFWL, EXT) + (kCWL \cdot CWL \cdot cCWL, EXT) - (kEXT \cdot EXT)$$

$$\frac{d\,CEL}{d\,t} = (uNWL \cdot cNWL, CEL) + (kFWL \cdot FWL \cdot cFWL, CEL) + (kCWL \cdot CWL \cdot cCWL, CEL) - (pEXT \cdot kCEL \cdot CEL) - \big((1 - pEXT) \cdot kCEL \cdot CEL\big)$$

$$\frac{d\,LIG}{d\,t} = (uNWL \cdot cNWL, LIG) + (kFWL \cdot FWL \cdot cFWL, LIG) + (kCWL \cdot CWL \cdot cCWL, LIG) + (pEXT \cdot kEXT \cdot EXT) + (pCEL \cdot kCEL \cdot CEL) - (pLIG \cdot kLIG \cdot LIG) - \big((1 - pLIG) \cdot kLIG \cdot LIG\big)$$

$$\frac{d\,HUM1}{d\,t} = (pLIG \cdot kLIG \cdot LIG) - (kHUM1 \cdot HUM1)$$

$$\frac{d\,HUM\,2}{d\,t} = (pHUM1 \cdot kHUM1 \cdot HUM1) - (kHUM2 \cdot HUM2)$$

Where:

- $u\{i\}$ is the input of litter type *i* to the the system (*i* = *fine woody litter (FWL), coarse woody litter (CWL))*
- $k\{i\}$ or $k\{j\}$ is the rate of decomposition of litter type *i* or decomposition compartment *j*
- $c\{i,j\}$ is the concentration in of compounds *j* in litter type *i*

- $p\{j\}$ *is* the proportion of mass decomposed in compartment *j* transferred to a subsequent compartment the rest is lost.

The non-woody litter is released all in one year, and its content is allocated to the first three decomposition compartments (equation 1).

$c(ij)$ values are provided by the model, there are two set of these parameters, one for conifers and the other for deciduous trees. The $p(j)$ values are fixed to 0.2 in the model.

The elative decomposition rate $k_{\{i\}}$ or $k_{\{j\}}$ increase with higher air temperatures and moist and decreases with increasing summer drought, according to the following equation:

$$k_{i/j(T,D)} = k_{\{i/j\}0}\left(1 + s * 0.000387\,(T - 1903) + 0.00325\,(-D - (-32))\right)$$

Where:

$k_{\{i/j\}0}$ are the relative decomposition rates under the chosen standard conditions (effective temperature sum= 1903 °C, and summer rainfall deficit D= -32 mm). These are intrinsic in the model, and specific for each litter and decomposition compartment.

T is the effective temperature sum (sum of the degree above 0°C throughout the year) and D is the summer rainfall deficit (precipitation minus evapotranspiration from May to September).

Table 4 Soil module fixed parameters (Liski et al., 2005).

Parameter	Value
Decomposition of fine woody litter (K_{fwl})	0.54
Decomposition of corse woody litter (K_{cwl})	0.03 or 0.077
Decomposition of extractives (K_{ext})	0.48 (conifers) or 0.82 (decidous)
Decomposition of cellulose (K_{cel})	0.30
Decomposition of lignin-like (K_{lig})	0.22
Decomposition of humus 1 (K_{hum1})	0.012
Decomposition of humus 2 (K_{hum2})	0.0012
Extractives to ligninlike (p_{ext})	0.2
Cellulose to Lignin-like (p_{cel})	0.2
Lignin-like to humus 1 (p_{lig})	0.2
Humus 1 to humus 2 (p_{hum1})	0.2

Table 5 Concentration of compound type (extractive, cellulose, or lignin-like) in litter type (non woody, fine woody, coarse woody. In conifers. (Liski et al., 2005).

	extractives	Cellulose	Lignin-like
Non woody litter	0.27	0.51	0.22
Fine woody litter	0.03	0.65	0.34
Coarse woody litter	0.03	0.69	0.28

Table 6 Concentration of compound type (extractive, cellulose, or lignin-like) in litter type (non woody, fine woody, coarse woody. In deciduous. (Liski et al., 2005).

	extractives	Cellulose	Lignin-like

Non woody litter	0.38	0.36	0.26
Fine woody litter	0.03	0.65	0.32
Coarse woody litter	0.03	0.75	0.22

Appendix 4 Wood densities per species

Table 7 Wood densities per species (IPCC,2003)

Species	Wood density (Mg DM ha^{-1})
Scots pine (*Pinus sylvestris*)	0.42
Oak (*Quercus robur*)	0.51
Birch (*Betula pendula*)	0.58
Douglas fir (*Pseudotsuga menziesi*)	0.45
Japanese larch (*Larix kaempferi*)	0.49

Appendix 5 Competition relative to total biomass in the stand and Bmax PB scenario

The following table shows growth modifiers factors at each actual above ground biomass over maximum aboveground biomass. All the missing points are interpolated automatically by CO2FIX.

Table 8 Growth modifier at each Total Biomass/ Maximum Biomass ratio used to depict competition

Biomass in the stand/Maximum Biomass	Growth modifier
0	1
0.2	1
0.6	0.9
0.8	0.7
0.9	0.5
1	0

The maximum biomass in the stand B_{max} of the PB scenario is set to 415 t DM ha^{-1} calculated as follow:

$$B_{max} = V_{max} \times d \times \frac{AGB}{Bstem} = 708\ m^3 ha^{-1} \times 0.45\ tDM\ m^{-3} \times 1.3 = 415\ tDM\ ha^{-1}$$

Where V_{max} = 708 m^3 ha^{-1} is taken from the yield table for Douglas fir (site class III, 120 years) assuming that the most productive tree species in the stand is the one that defines the stand maximum biomass. *d* is the basic wood density (0.45 t DM m^{-3}); and AGB/stem is the ratio of above ground biomass and stem biomass, assumed as 1.3 in this case (Jansen and Oosterbaan 2018;IPPC 2003) .

Appendix 6 Harvest allocation factors

Stems

- 15% slash at all diameters.
- No logwood below 10 cm.
- Logwood fractions by diameter:

Diameter stem (cm	fraction
10	0.05
15	0.15
20	0.35
50	0.60

- Remainder = pulpwood.

Branches

- *Conifers and short-rotation angiosperms*: no logwood; pulpwood increases from 0.1 at 5 cm to 0.5 at ≥50 cm, remainder = slash.
- *Long-rotation angiosperms (e.g. oak)*: pulpwood = 0.3 from 20 cm onwards; logwood increases from 0.05 at 15 cm to 0.2 at ≥50 cm; remainder = slash.

NB The rest of the points both for stems and branches are interpolated with a midpoint allocation rule. Fractions were averaged between the lower and upper threshold. For example, if logwood fraction was 0.05 at 10 cm and 0.15 at 15 cm, the value for 12.5 cm was set as the midpoint (0.10). This stepwise approach avoids excessive precision that the data cannot support.

Appendix 6 Product parameters

Table 9 Raw material allocation in high efficiency processing and recycling and in low efficiency processing and recicling. Outside brackets high efficiency and inside brackets low efficiency (Schelhaas et al., 2004)

RAW MATERIAL	Sawwood	Boards	Paper	Firewood
Logwood	0.8 (0.2)	0.15 (0.3)	0.05 (0.1)	0 (0.4)
PulpWood		0.05 (0.0)	0.9 (0.8)	0.05 (0.2)

Table 10 Process losses allocation in high efficiency processing and recycling and in low efficiency processing and recicling. Outside brackets high efficiency and inside brackets low efficiency (Schelhaas et al., 2004)

PRODUCTION LINE	Boards	Paper	Firewood	Mill site dump
Saw wood	0.4 (0.1)	0.3 (0.12)	0.2 (0.35)	0 (0.2)

Boards		0.6 (0.05)	0.1 (0.2)	0 (0.2)
Paper			0.3 (0.2)	0 (0.2)
Firewood				1 (0.05)

Table 11 Product allocation to long,medium and short term end of life. in high efficiency processing and recycling and in low efficiency processing and recicling. Outside brackets high efficiency and inside brackets low efficiency (Schelhaas et al., 2004)

PRODUCTION LINE	**Long term**	**Medium term**	**Short term**
Sawnwood	0.5 (0.1)	0.25 (0.4)	0.25 (0.5)
Boards	0.3 (0.1)	0.5 (0.3)	0.2 (0.6)
Paper	0.01 (0.0)	0.1 (0.04)	0.89 (0.96)

Table 12 End of life destination of the product types. allocation in high efficiency processing and recycling and in low efficiency processing and recicling. Outside brackets high efficiency and inside brackets low efficiency (Schelhaas et al., 2004)

PRODUCT TYPE	**Recycling**	**Energy**	**Landfill**
Long term	0.3 (0.02)	0.1 (0.3)	0.6 (0.68)
Medium term	0.1 (0.04)	0.1 (0.3)	0.8 (0.66)
Short term	0.4 (0.15)	0.5 (0.4)	0.1 (0.45)

Table 13 recycling destination product type to product typer fractions. allocation in high efficiency processing and recycling and in low efficiency processing and recicling. Outside brackets high efficiency and inside brackets low efficiency (Schelhaas et al., 2004)

PRODUCT TYPE	**Long term**	**Medium term**	**Short term**
Long term	0.1 (0.0)	0.3 (0.2)	0.6 (0.8)
Medium term		0.1 (0.1)	0.9 (0.9)
Short term			0 (0)

Table 14 Half life per product type in years (Schelhaas et al., 2004)

PRODUCT TYPE	**Half life [year]**
Long term	30 (20)
Medium terms	15 (10)
Short term	1 (1)
Mill site dump	5 (10)
Landfill	145 (145)