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Life Cycle Assessment of Peat Extraction Towards Peat-bog Reconversion Strategies: Scenarios Comparison Based on a Real Case Study from a Latvian Peat Extraction Factory

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***Abstract* – This study evaluates the environmental and economic performance of alternative reconversion strategies for drained peatlands following industrial extraction, using a real case study from Latvia. In alignment with the EU Nature Restoration Law, three main restoration pathways were analysed (i.e., renaturalization, afforestation, and blueberry cultivation), each modelled through a 100-year Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) framework. The LCA focused on greenhouse-gas (GHG) emissions, while the economic assessment included implementation costs, revenues, and the monetary value of ecosystem services. Results show that maintaining drained peatlands is the most unsustainable option (756.65 t CO_2 eq ha^{-1}). Renaturalization and blueberry cultivation reduce emissions by 225.49 t CO_2 eq ha^{-1} and 258.45 t CO_2 eq ha^{-1}, respectively, whereas afforestation demonstrates the highest mitigation potential, achieving carbon neutrality after 67 years and a net GHG uptake of 310.09 t CO_2 eq ha^{-1} by year 100. Integrating renewable-energy systems further enhances performance, with afforestation combined with solar or wind installations yielding additional avoided emissions exceeding 500 t CO_2 eq ha^{-1}. Economically, blueberry cultivation provides the largest direct revenues, while afforestation yields the highest carbon-credit value. However, when ecosystem services are monetized, renaturalization becomes the most beneficial strategy, reaching a cumulative value of € 31.2 million ha^{-1}. Overall, the study highlights that combining LCA and LCC provides robust decision support for sustainable peatland management, demonstrating that rewetting and afforestation can effectively balance climate-mitigation goals with socio-economic viability. Furthermore, the economic outcomes are strongly influenced by the ecosystem-service monetisation methodology used; the assumptions and limitations of this approach are now fully clarified in the Methods and discussed as a source of uncertainty. Given the limited availability of long-term field data, the analysis is based on deterministic scenarios without explicit uncertainty ranges, variability estimates, or sensitivity analyses. Likewise, N_2O fluxes could not be included due to the lack of robust, site-specific emission factors for restored peatlands.**

***Keywords* – Ecosystem services; greenhouse-gas emissions; Life Cycle Assessment; peatland restoration.**

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1. INTRODUCTION

Peatlands, covering approximately 3 % of the Earth's land surface, are unique wetland ecosystems that play a central role in the global carbon cycle and climate regulation. They occur mainly in the Northern Hemisphere (i.e., North America, Russia, and Europe) and are characterized by the long-term accumulation of organic matter (peat) under water-saturated, anoxic conditions that slow decomposition [1]–[3]. The layered peat profile consists of an upper, seasonally aerated acrotelm and a permanently saturated catotelm, where biomass decays extremely slowly, allowing peat deposits to reach several meters in thickness over millennia [2]. Peat formation occurs when primary production exceeds decomposition rates in hydrologically confined areas such as fens, bogs, and transitional mires [4]. These systems develop where precipitation surpasses evapotranspiration, and geomorphology favours water retention [5].

Despite their limited extent, peatlands store between one-third and one-half of global soil carbon, up to 550 Gt C, more than twice the carbon stock of all forest biomass [6], [7]. Their waterlogged conditions make them long-term carbon sinks, removing atmospheric CO_2 through photosynthesis and peat accumulation while emitting moderate quantities of CH_4 and negligible N_2O [8], [9]. Consequently, they provide critical ecosystem services for climate-change mitigation, hydrological regulation, biodiversity conservation, and cultural value [4], [10].

Peatlands deliver provisioning services such as berries, honey, fish, and plant materials (*Typha*, *Sphagnum*) for food, medicine, and construction; regulating services including water purification, flood control, and carbon sequestration; and cultural services linked to recreation, education, and paleo-environmental archiving [2], [10]. However, centuries of drainage for agriculture, forestry, and fuel or horticultural peat extraction have degraded about 50 million ha worldwide, turning many sites from carbon sinks into major GHG sources [4]. In Europe, more than half of all peatlands are drained, accounting for roughly 7 % of total EU-27 annual GHG emissions [11].

The restoration and sustainable management of degraded peatlands have therefore become both an environmental and economic priority. The recently adopted EU Nature Restoration Law [12] requires Member States to restore at least 50 % of drained peatlands by 2050, recognizing their pivotal role in achieving carbon neutrality. Yet, the transition from extraction-based land use to restoration and bio-based activities requires systematic evaluation of environmental and financial trade-offs.

In this framework, the present research applies a combined Life Cycle Assessment (LCA) and economic evaluation approach to identify the most sustainable reconversion pathways for peat extraction areas. LCA provides a quantitative evaluation of greenhouse-gas emissions and other environmental burdens associated with different restoration strategies, such as renaturalization, afforestation, and blueberry cultivation, over a 100-year horizon, while the economic dimension is integrated by assessing investment and maintenance costs as well as ecosystem-service benefits. The integration of these complementary tools enables a complete assessment of the environmental and economic feasibility of peatland reconversion scenarios, providing scientific evidence to guide policymakers and stakeholders in selecting strategies that maximize carbon sequestration, minimize emissions, and ensure long-term socio-economic viability.

2. Methodology

2.1. The Peatlands Reclamation Strategies in the Context of the EU Natural Restoration Law

The continuous degradation of European ecosystems, with more than 80 % of habitats being in poor condition, has led to the approval of the EU Nature Restoration Law [12], the first continent-wide regulation aimed at reversing biodiversity loss and enhancing carbon sequestration. The law mandates Member States to restore at least 20 % of EU land and sea areas by 2030, progressing to all degraded ecosystems by 2050, and specifically targets drained peatlands for rewetting (i.e., renaturalized) and restoration. By 2050, 50 % of drained peatlands must be restored, with at least one-third rewetted, as these ecosystems can significantly reduce net greenhouse-gas emissions and support the EU's carbon-neutrality objectives [11], [12].

There are several after-use strategies to reclaim peatlands previously used for extraction or agriculture, with different techniques tailored to the hydrological and chemical conditions [13]. In this manuscript, the term "renaturalization" is used consistently to refer to the combined hydrological rewetting and ecological restoration of peatlands. The term "rewetting" is used exclusively when referring to the hydrological operation in a strict sense.

The renaturalization or rewetting of peatlands seeks to re-establish the original hydrology and vegetation by blocking drainage ditches and re-introducing *Sphagnum* communities, transforming degraded sites back into carbon-accumulating mires. Alternatively, afforestation creates managed woodlands that combine carbon uptake in tree biomass with moderate reductions in soil emissions, providing economic returns from timber. Blueberry plantations on raised bogs represent an economically attractive Paludiculture option, ensuring low-emission land use while maintaining partial drainage control [14]. Other possible after-uses include Paludiculture with reeds or cattails for bio-based products, creation of water bodies for biodiversity and recreation, and perennial grasslands for biomass production [13].

2.2. Case Study Description

Latvia hosts one of the highest proportions of peat soils in Europe, covering approximately 11.7 % of the national territory [15] (Fig. 1). Peat extraction represents a historically and economically significant activity, with around 1.25 million tonnes of peat harvested annually, supplying nearly 31 % of the horticultural peat used within the European Union [16]. However, long-term extraction and drainage have led to substantial degradation of these ecosystems, resulting in elevated GHG emissions and loss of biodiversity [13].

In alignment with the objectives of the EU Nature Restoration Law [12], this study focuses on identifying and evaluating alternative land-use strategies for post-extraction peatlands in Latvia.

The analysis compares the environmental and economic performance of different peatland reconversion strategies against a degraded reference scenario, referred to as the baseline, representing a drained and extracted raised bog with the catotelm layer exposed to air. Such areas, typical of industrial peat extraction sites, are known to act as significant carbon sources. The comparison is carried out through an LCA and Life Cycle Costing (LCC) framework to assess both greenhouse-gas emissions and the associated financial implications over a 100-year time horizon.

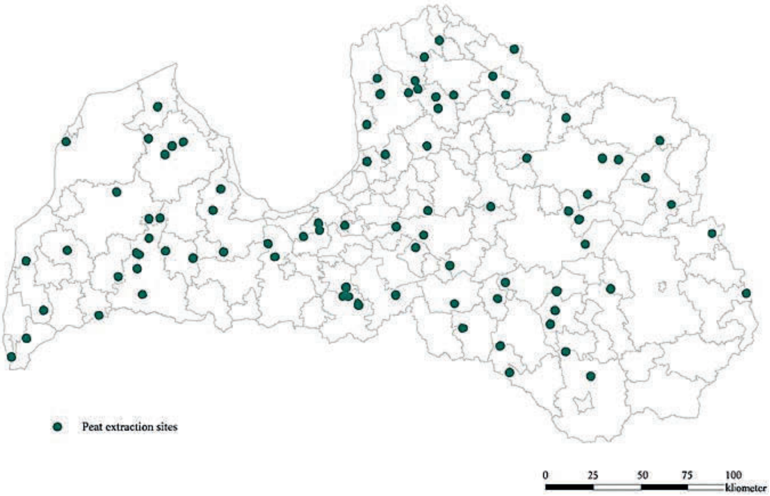

Fig. 1. Distribution of peatlands in Latvia. Readapted from [16].

Only CO_2 and CH_4 fluxes are considered in this study due to the limited availability of data on N_2O dynamics following restoration. Although N_2O emissions can be relevant in fertilised systems such as afforestation and blueberry cultivation, robust and comparable emission factors for post-extraction peatlands in the Latvian context are not available for all scenarios. Including partial or inconsistent data would introduce significant methodological bias. Therefore, N_2O was excluded from the quantitative modelling, and the potential implications of this omission, both under- and over-estimation, are explicitly discussed as a limitation. The LCA approach accounts not only for the natural emissions and sequestration processes occurring within each land-use type but also for the upstream emissions associated with restoration and maintenance activities (e.g., land preparation, machinery use, or planting operations). Economic aspects include both the implementation costs of each reconversion and the monetary valuation of ecosystem services where applicable.

To ensure transparency, a constant real discount rate of 3 % per year was applied to all future costs and revenues. Net present value (NPV) was calculated following the standard formulation:

$$NPV = \sum_{t=1}^{n} \frac{\left(B_t - C_t\right)}{\left(1+r\right)^t} , \tag{1}$$

where

NPV	(Net Present Value): total value in present terms of all future benefits and costs associated with the project. It is used to determine whether a project is economically viable.
B_t	(Benefits at time *t*): all positive cash flows or revenues generated in year *t* (e.g., sales, carbon credits, ecosystem service value).
C_t	(Costs at time *t*): al negative cash flows in year *t* (e.g., investment, maintenance, operational costs).
R	(Discount rate): to convert future costs and benefits into their present value.
$(1 + r)^t$	the discount factor**,** which reduces future values to make them comparable with present values.

The monetisation of ecosystem services relies on benefit-transfer methods and local willingness-to-pay estimates derived from previous studies on Latvian peatlands. While robust, this methodology carries inherent epistemic uncertainties that may influence overall economic rankings.

2.2.1. Case study strategies selection

Among the restoration and after-use options described in the literature [13]. Three representative scenarios were selected based on their ecological relevance, data availability, and potential applicability to the Latvian context:

- *Renaturalization (Rewetting)*: Restoration of natural hydrological conditions and re-establishment of peat-forming vegetation (*Sphagnum* spp.), aiming to recreate the original mire ecosystem and reinitiate long-term carbon accumulation.
- *Blueberry Cultivation*: Establishment of highbush blueberry (*Vaccinium corymbosum*) plantations on raised bogs under controlled moisture conditions, representing a form of Paludiculture with proven economic profitability in Latvia [14]. In this section, the expression "renaturalization (rewetting)" is used only to reflect terminology contained in existing policy documents; however, throughout the rest of the manuscript "renaturalization" is adopted as the standard and unambiguous term.
- *Afforestation*: Conversion of degraded peatlands into Scots pine (*Pinus sylvestris*) stands, combining carbon storage in biomass with potential timber revenue [17].

For the cultivation and afforestation cases, additional integrated energy scenarios were developed by coupling land restoration with renewable-energy generation, specifically, solar photovoltaic and wind turbine installations. These hybrid options aim to explore synergies between ecosystem restoration and low-carbon energy production. To maintain ecological integrity and comply with the EU restoration targets, renewable-energy infrastructure was assumed to occupy a maximum of 25 % of the total restored area, applying a conservative approach.

The assumption that renewable-energy installations may occupy no more than 25 % of the land area is a modelling choice rather than a regulatory constraint. It reflects a conservative balance between ecological restoration and low-carbon energy production.

The renaturalization scenario was not coupled with energy systems, as its primary goal is the complete recovery of natural ecosystem functions without anthropogenic disturbance.

2.3. CO_2 and CH_4 Emissions Data Collection

A comprehensive literature review was conducted to quantify CO_2 and CH_4 fluxes associated with each peatland land-use scenario. The data selection focused exclusively on raised bog peatlands located in Nordic regions, including both European and Canadian case studies, as their climatic conditions closely resemble those of Latvia. To ensure consistency with the case study context, only sources referring to extraction-affected bogs were considered, excluding generic drained or agricultural peatlands.

For the renaturalization scenario, the analysis accounted for the temporal evolution of ecosystem gas exchanges following restoration. Emission data were compiled for four time intervals: 3, 10, 25, and 50 years after rewetting. Representing the progressive recovery of hydrological and biological conditions. After 100 years, GHG emissions were assumed to converge with those of a natural bog ecosystem.

In contrast, limited empirical data were available for blueberry cultivation systems. Consequently, emissions were assumed constant over time at 4.97 t CO_2 eq ha^{-1} yr^{-1} [13].

Due to the lack of long-term empirical observations for blueberry cultivation systems on post-extraction peat soils, this constant-value approach represents a steady-state approximation rather than a true temporal emission trajectory. This simplification may weaken comparability with scenarios that incorporate explicit temporal dynamics and is therefore acknowledged as a methodological limitation.

For the afforestation scenario, the Net Ecosystem Exchange (NEE) of Scots pine (*Pinus sylvestris*) was modelled across a 100-year growth cycle [18] and combined with the soil-emission component of an afforested peatland, yielding the total ecosystem GHG balance for this land-use type.

2.4. Life Cycle Assessment Approach

2.4.1. Goal and scope definition

The environmental performance of the proposed peatland reconversion strategies was evaluated through an LCA focusing on GHG emissions. The analysis targeted the impact category Global Warming Potential (GWP 100) over a 100-year time horizon, using the IPCC 2021 GWP 100 characterization method to express all emissions in CO_2 equivalents (CO_2 eq.).

This comparative LCA aims to assess and compare the sustainability of multiple after-use scenarios, providing decision support for peat extraction companies and policymakers in selecting strategies that minimize climate impacts. The functional unit (FU) was defined as 1 hectare of peatland area, ensuring a consistent reference for all system comparisons.

System boundaries for renaturalization, blueberry cultivation, and afforestation scenarios included all processes related to site preparation, planting, and maintenance. In scenarios integrating renewable-energy systems (solar photovoltaic and wind turbines), boundaries were expanded to include infrastructure construction and electricity generation, enabling an evaluation of potential GHG offset benefits.

Primary data were derived from literature sources, while background data for materials, energy, and transport processes were obtained from the *SimaPro 9.5* software coupled with the *Ecoinvent 3* database (allocation, cut-off by classification, unit). The allocation approach enables consistent impact comparison among co-products, while the cut-off principle excludes recycled inputs. Whenever possible, processes were adapted to the Latvian geographical context, and market datasets were employed to account for product transport from producer to consumer.

Due to limited long-term empirical data, the LCA and LCC results are expressed as deterministic scenario outcomes without uncertainty ranges or sensitivity analyses. The implications of this constraint are discussed in the Conclusions, and the results should be interpreted as comparative indicators rather than predictive values.

2.4.2. Systems description and Life Cycle Inventory

The system descriptions with the related LCI are reported below:

– *Renaturalization scenario (baseline)*

The renaturalization plan was divided into eight operational phases, each modelled as a discrete process in the LCA framework: (1) site preparation through surface levelling and ditch filling to restore hydrological uniformity; (2) collection of donor plant material, mainly *Sphagnum* mosses, from nearby intact bogs; (3) pick-up and transportation of the plant fragments; (4) plant spreading over the restoration area to ensure a continuous vegetative cover; (5) application of straw mulch (~3 t ha^{-1}) for moisture retention; (6) fertilization with phosphorus-based compounds (150 kg ha^{-1}) to promote initial growth; (7) ditch blocking using compacted peat dams to re-establish the natural water table; and (8) creation of small water pools (~0.7 per ha) to enhance habitat diversity. More information is available in the supplementary material.

Diesel consumption for machinery was estimated based on analogous agricultural operations [19] and detailed in Table 1.

TABLE 1. RENATURALIZATION PHASES WITH THE RELATED AGRICULTURAL PROCESSING AND DIESEL CONSUMPTION

Phase	Equipment	Agricultural processing	Diesel amount, L/ha
Site preparation	Leveller	Levelling of the rice field	11.08
Plant collection	Rotovator	Rolling of the grassland	7.39
Plant pick-up	Windrow rake	Windrowing of the herb garden	12.01
Plant spreading	Standard box manure	Manure application in grassland	12.93
Straw spreading	Sideways straw spreader	Manure application in grassland	22.62
Fertilization	Conic spreader	Weeding of rice fields	12.01

– *Blueberries plantation*

For the blueberry cultivation scenario, five main operational phases were modelled [13]: (1) The process begins with site preparation, during which the peatland surface is levelled and milled to create a smooth topography that minimizes frost risk and optimizes the soil moisture regime; existing trees and shrubs are removed to facilitate machinery operation. Once prepared, the surface is shaped into furrows measuring approximately 0.5 m in height, 0.7 m in width, and spaced 3 m apart. (2) The drainage system is then modified to maintain the groundwater table between 0.35 and 0.55 m below the surface by either blocking existing ditches or constructing new ones, depending on hydrological conditions. (3) Small pools are subsequently created to stabilize the site's water balance and provide a supplementary irrigation source. (4) The next phase involves fertilization with superphosphate and potassium–magnesium oxide, each applied at 160 kg ha^{-1}, to enhance nutrient availability in the acidic peat substrate. (5) Finally, manual planting is carried out with approximately 2500 highbush blueberry (*Vaccinium corymbosum*) seedlings per hectare, spaced 1 m apart and sourced primarily from Poland. The diesel consumptions for the operations are summarized in Table 2.

TABLE 2. BLUEBERRY PLANTATION PHASES WITH THE RELATED AGRICULTURAL PROCESSING AND DIESEL CONSUMPTION

Phase	Equipment	Agricultural processing	Diesel amount, L/ha
Site preparation	Leveller	Levelling of the rice field	11.08
Fertilization	Conic spreader	Weeding of rice fields	25.62

– *Afforestation*

For the afforestation scenario, five main operational phases were modelled [13]. (1) The process begins with site preparation, during which ditch berms are levelled, and the existing vegetation cover is removed to facilitate tree planting and ensure uniform soil conditions. (2) The drainage system is then modified to maintain the groundwater level below 0.35 m from the surface, adapting the existing network according to the degree of prior peatland drainage to guarantee adequate aeration for root development. (3) Fertilization follows, addressing the nutrient-poor nature of raised bog soils by applying fertilizers rich in phosphorus (10 t ha^{-1}) and nitrogen (4 t ha^{-1}); organic fertilizers are preferred due to their higher effectiveness compared to mineral formulations [20]. The fertiliser application rates adopted for the afforestation scenario represent a conservative upper-bound estimate. These values may exceed typical forestry practice and therefore likely overestimate both emissions and costs. They are intended to model a 'worst-case' establishment strategy and are explicitly recognised as such. (4) The plantation phase involves either manual or mechanical planting of tree seedlings, arranged in rows at least 1.5 m apart. For Scots pine (*Pinus sylvestris*), approximately 1000 seedlings per hectare are established to ensure optimal growth density. (5) Finally, management activities are carried out during the first five years to protect young trees from ungulate browsing, using repellents, protective tubes, or, more cost-effectively, perimeter fencing around the afforested area.

TABLE 3. AFFORESTATION PHASES WITH THE RELATED AGRICULTURAL PROCESSING AND DIESEL CONSUMPTION

Phase	Equipment	Agricultural processing	Diesel amount, L/ha
Site preparation	Leveller	Levelling of the rice field	11.08
Fertilization	Conic spreader	Weeding of rice fields	1120.93

– *Solar power production*

To assess the integration of renewable energy into peatland reconversion, the study evaluated the installation of solar photovoltaic (PV) systems within the blueberry cultivation and afforestation scenarios. The selected technology was a monofacial crystalline silicon PV module, chosen for its high efficiency and commercial availability [21].

The analysis began by estimating the panel density per hectare, based on three reference solar parks in Italy [22]. An average of 1 403 panels ha^{-1} was determined, each with a nominal capacity of 0.53 kW, resulting in an installed power of approximately 754 kW ha^{-1}. Using the European Commission's PVGIS performance tool [23], and assuming installation in Latvia with 14 % system losses, the estimated annual electricity yield was 740.908 kWh yr^{-1}. Solar panels were assumed to have a 25-year lifespan, requiring four replacements over the 100-year assessment period. To align with the Nature Restoration Law's ecological constraints, the solar plant was modelled to occupy 25 % of the total land area, while the remaining 75 % was dedicated to the restoration activity (blueberry cultivation, afforestation or, in case, renaturalization). The assumed 25-year lifetime for PV modules corresponds to standard warranty periods and widely used LCA benchmarks. Although no sensitivity analysis was carried out on the lifetime parameter, its effect, particularly through periodic replacement cycles, is acknowledged qualitatively in the Results section. In the LCA model, electricity generation was treated as an avoided product, substituting power from the Latvian energy mix, which still partly relies on fossil fuels, thus representing a GHG benefit.

– *Wind power plant*

The integration of wind energy generation into peatland reconversion strategies was modelled analogously to the solar power plant scenario, with the goal of assessing potential GHG offset benefits from on-site renewable electricity production.

The selected turbine type featured a 2 MW rated capacity and a 100 m rotor diameter. Power output was calculated using the standard aerodynamic equation, ($0.5 \times C_p \times \rho \times A \times v^3$) where the power coefficient (C_p) was set to 0.39 [24], (ρ) air density to 1.225 kg m^{-3}, and mean wind speed (v) to 4.76 m s^{-1}, corresponding to average conditions recorded in Jelgava, Latvia [25].

The resulting annual energy yield for a single turbine was estimated at 1778 MWh yr^{-1}. Based on aerodynamic spacing requirements of 5.62 rotor diameters between turbines [26] each unit was assumed to occupy 24.79 ha, resulting in an effective energy density of approximately 71.7 MWh ha^{-1} yr^{-1}. As in the solar scenario, the wind turbine life span was set at 25 years, implying four reconstructions over the 100-year analysis period. The power plant occupied 25 % of the total land area, while the remaining 75 % was dedicated to blueberry cultivation or afforestation. Also in this case, electricity generation was modelled as an avoided product, substituting fossil-based electricity from the Latvian energy mix.

2.5. Economic Evaluation

In addition to the environmental assessment, an economic evaluation was performed to determine the financial feasibility of each peatland reconversion strategy over a 100-year time horizon.

For each scenario, renaturalization, blueberry cultivation, and afforestation, the total investment included site preparation, planting, fertilization, infrastructure construction, and maintenance activities.

Revenues were derived from marketable outputs and ecosystem services. Blueberry cultivation generated direct income from berry production, while afforestation accounted for the timber value of mature *Pinus sylvestris* stands. In renaturalization, economic benefits were expressed through the monetary valuation of ecosystem services, such as carbon sequestration and biodiversity enhancement.

Cost and benefit data were compiled from literature sources and national market statistics [13], [27], converted to EUR ha^{-1} and discounted over time. The complete list of costs and benefits is reported in the supplementary material. The LCC results were compared across all reconversion options to identify those delivering the highest long-term economic returns in parallel with GHG reduction benefits.

3. RESULTS

3.1. Peatland Emissions Results

3.1.1. Renaturalization scenario

In Fig. 2 there are reported trends for CO_2 and CH_4 emissions. The CO_2 emissions initially increase during the early restoration phase, reaching a peak between the third and ninth year with an average release of 17.53 t CO_2 ha^{-1} yr^{-1}. This short-term rise is attributed to microbial oxidation of residual peat and decomposition of organic matter under newly rewet conditions. From the tenth year onward, emissions progressively decline, becoming negative after approximately 25 years, when the restored peatland begins to act as a net carbon sink with an uptake of 2.49 t CO_2 ha^{-1} yr^{-1}. After a century, the system stabilizes to values typical of natural bogs, maintaining a sustained CO_2 uptake of 1.20 t CO_2 ha^{-1} yr^{-1}.

Conversely, CH_4 emissions display an opposite dynamic, increasing steadily for the first 50 years due to enhanced anaerobic activity and reaching a maximum of 11.25 t CO_2 eq. ha^{-1} yr^{-1} before gradually decreasing but remaining a persistent methane source at about 1.79 t CO_2 eq. ha^{-1} yr^{-1} after 100 years. When both gases are integrated (Fig. 3), the peatland remains a net GHG emitter of 0.58 t CO_2 eq. ha^{-1} yr^{-1}.

However, when compared to a drained peatland (Fig. 3), renaturalization yields a cumulative GHG reduction of 225.49 t CO_2 eq. ha^{-1} over 100 years, confirming its long-term climate mitigation potential despite short-term emission peaks.

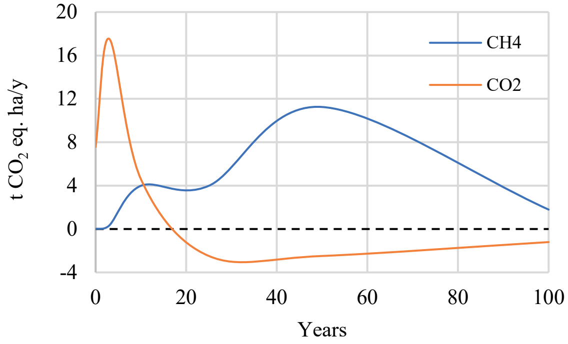

Fig. 2. CO_2 and CH_4 emissions from the renaturalized peatland over the 100-year period.

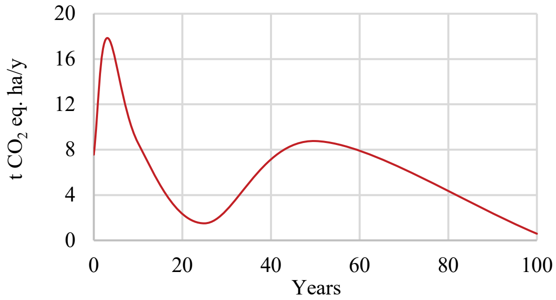

Fig. 3. Total normalized emissions (CO_2 + CH_4) from a renaturalized peatland.

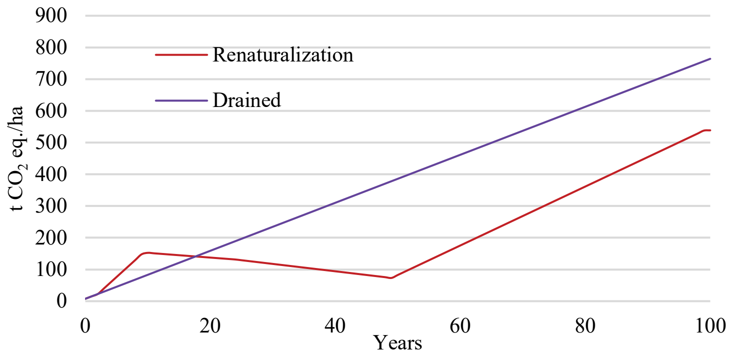

Fig. 4. Cumulative emissions comparison between drained and renaturalized peatland.

3.1.2. Blueberry plantation and afforestation

For the blueberry cultivation scenario, GHG emissions were assumed to remain constant over time, as described in Chapter 2.3, with an estimated release of 4.97 t CO_2 eq. ha^{-1} yr. Due to the absence of temporal variation, no emission evolution charts were generated.

In contrast, the afforestation scenario shows a dynamic emission profile strongly influenced by the growth stages of *Pinus sylvestris* (Fig. 5). Immediately after establishment, GHG emissions reach 17.59 t CO_2 eq. ha^{-1} yr^{-1}, mainly due to soil disturbance and initial microbial activity. Emissions then decrease progressively as tree biomass and soil carbon stocks increase, becoming negative after approximately 25 years, when the system transitions to a net carbon sink. After 100 years, the annual CO_2 uptake reaches 11.97 t CO_2 eq. ha^{-1} yr^{-1}. Cumulative results (Fig. 6) indicate that net GHG neutrality is achieved after about 65 years, when total emissions are fully compensated by sequestration, and that by the end of the 100-year assessment, the afforested peatland has accumulated a GHG uptake of 327.09 t CO_2 eq. ha^{-1}, confirming its strong long-term climate mitigation potential.

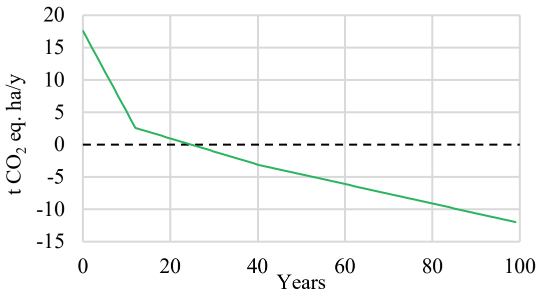

Fig. 5. GHG emissions from the afforested peatland over the 100-year period.

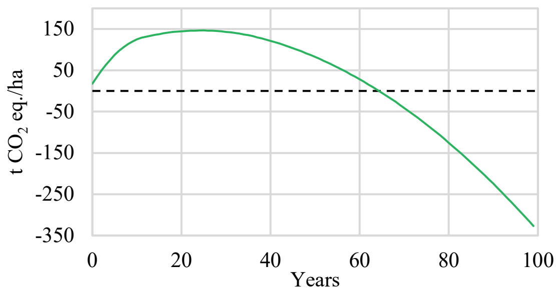

Fig. 6. Total cumulative emission for the afforested peatland.

3.2. LCA Results

3.2.1. Comparison between different restoration scenarios – technological aspects

In Fig. 7, the comparison of all the different scenarios included in the study is reported. These first results were performed to quantify the technological implementation impacts of each reconversion strategy prior to including direct peatland GHG fluxes. This approach isolates the contribution of materials, energy use, and construction activities to the overall GWP.

For the renaturalization scenario, total emissions were estimated at 1.31 t CO_2 eq., with the phosphorus fertilizer supply as the main contributor (32.4 %), followed by grass silage use and diesel consumption. Transport processes had a negligible effect (0.89 %), reflecting the short distance assumed between collection and restoration sites.

In the blueberry plantation scenario, emissions reached 1.50 t CO_2 eq., largely dominated by the potassium fertilizer supply (53.1 %), while transportation again played a minor role (0.17 %), likely due to the low mass of planting material.

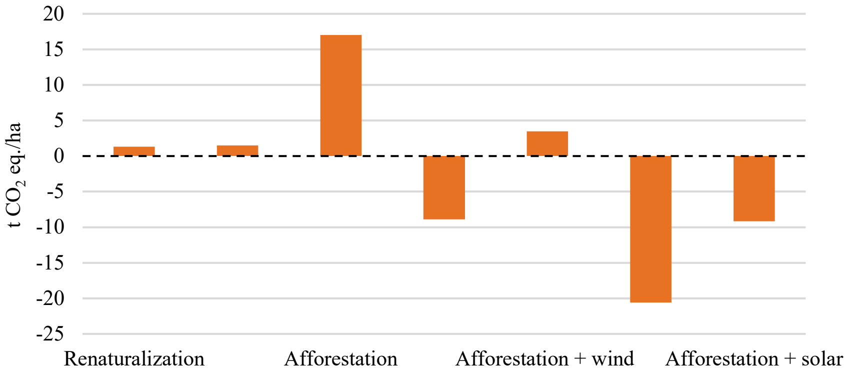

Fig. 7. Comparison of the technological impacts on the GWP for the different restoration scenarios.

The afforestation scenario resulted in higher impacts of 17 t CO_2 eq., mainly driven by the steel fence construction (34.9 %) and diesel use, while excavation contributed only 0.1 % due to limited earth movement.

When renewable energy integration was included, results improved significantly. The blueberry plantation with wind turbines achieved a net GHG uptake of −8.19 t CO_2 eq., as avoided emissions from electricity generation (9.32 t CO_2 eq.) exceeded construction impacts. The afforestation with wind turbines scenario remained slightly positive (3.46 t CO_2 eq.), indicating partial compensation.

In solar-powered configurations, both systems achieved strong GHG reductions: blueberry cultivation with PV panels yielded a net uptake of −20.6 t CO_2 eq., while afforestation with PV panels showed −9.18 t CO_2 eq. In both cases, the photovoltaic plant construction accounted for about 77 % of total emissions but was fully offset by the avoided fossil-based electricity. All figures were reformatted to improve resolution, clarity, and consistency. Terminology was standardised (e.g., CO_2 eq. notation), and language edits were implemented to ensure smoother readability throughout the manuscript.

3.2.2. Full LCA comparison on the classic reconversion strategies

Fig. 8 presents the results of the full LCA, combining both the technological implementation impacts and the direct GHG emissions from peatland ecosystems under different reconversion strategies. The comparison highlights substantial differences in long-term climate performance among the evaluated scenarios.

Maintaining the peatland in a drained condition represents the most unsustainable option, resulting in 756.65 t CO_2 eq ha^{-1} over 100 years. Continuous peat oxidation and decomposition under aerobic conditions make this the highest-emission baseline scenario. In contrast, blueberry cultivation performs moderately better, with total emissions of 498.20 t CO_2 eq ha^{-1}, achieving a GHG reduction of 258.45 t CO_2 eq ha^{-1} compared to the drained peatland. However, despite providing economic benefits, this land use remains a net emitter.

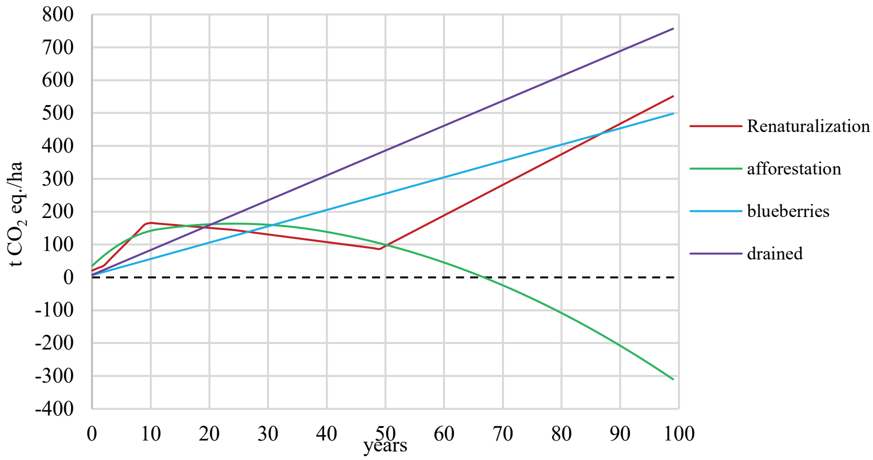

Fig. 8. Full LCA peatland reconversion strategies cumulative emissions.

The renaturalization scenario shows a similar improvement, with cumulative emissions reduction of 225.49 t CO_2 eq ha^{-1} relative to the drained condition.

The afforestation scenario demonstrates the best overall performance. Despite initially higher emissions from implementation and early soil processes, exceeding the drained peatland during the first two decades, the system transitions into a net carbon sink after year 26. Carbon neutrality is reached after 67 years, and by year 100, the afforested site achieves a net GHG uptake of 310.09 t CO_2 eq ha^{-1}, saving 446.56 t CO_2 eq ha^{-1} compared with the drained baseline.

3.2.3. Full LCA comparison on the energy production reconversion strategies

Fig. 9 presents the comparison of the full LCA impacts for the energy production reconversion strategies, which include solar and wind parks integrated within the blueberry cultivation and afforestation scenarios. The avoided emissions associated with renewable energy generation differ by several orders of magnitude (i.e., over 4000 t CO_2 eq./ha avoided over a 100-year period) compared to the ecosystem emissions, making their direct comparison impractical; therefore, they were excluded from the subsequent analysis.

As shown in the figure, all proposed reconversion strategies result in a reduction of GHG emissions over a 100-year period, even when the construction of the power plants is included. Among them, the solar power plant combined with blueberry cultivation represents the least favourable option, exhibiting cumulative emissions of 444.49 t CO_2 eq./ha, corresponding to a saving of 312.16 t CO_2 eq./ha compared to the baseline. The blueberry cultivation with a wind power plant scenario performs slightly better, with cumulative emissions of 369.93 t CO_2 eq./ha and an avoided emission of 386.72 t CO_2 eq./ha.

Consistent with the findings from the classic reconversion strategies, the afforestation scenarios show the best performance, achieving a net GHG uptake. Specifically, afforestation with a solar power plant results in a net uptake of 153.79 t CO_2 eq./ha, while afforestation with a wind power plant achieves an uptake of 228.12 t CO_2 eq./ha, corresponding to total avoided emissions of 528.53 t CO_2 eq./ha. The three distinct peaks observed in the curves of the solar-based scenarios are attributed to the periodic reinstallation of solar panels every 25 years.

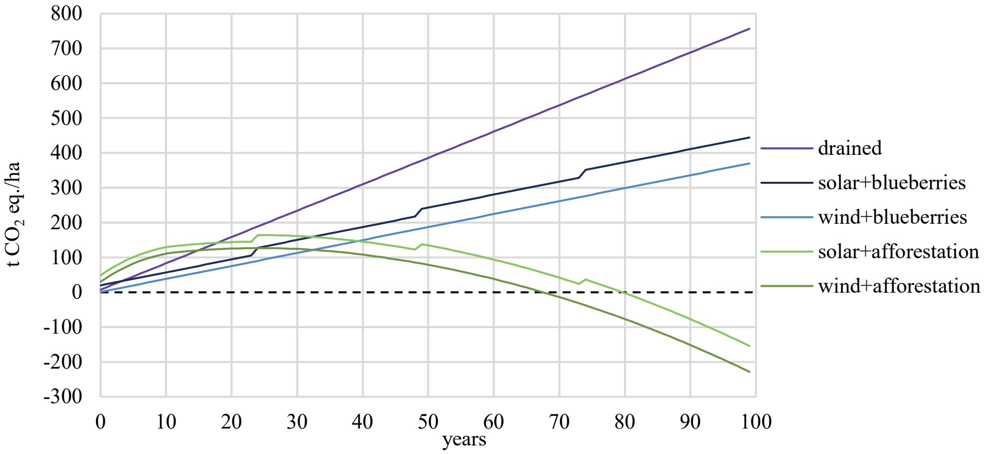

Fig. 9. Peatland reconversion strategies with electricity power plants' cumulative emissions.

3.3. Economic Results

In Table 4, the economic cost balances for the different reconversion strategies for the 100-year period are presented.

TABLE 4. CASHFLOW ANALYSIS FOR EACH RECONVERSION STRATEGY

	Reconversion cost	Carbon credits	Incomes
Renaturalization	−11 066 €	17 252 €	0 €
Blueberries	−76 612 €	21 751 €	1 196.000 €
Afforestation	−17 772 €	89 776 €	73 576 €

Among them, the blueberry plantation strategy is the most expensive to implement, with a cost of € 76 612/ha, while renaturalization is the least costly, at € 11 066/ha.

Despite the high initial investment, the blueberry plantation strategy offers substantial economic returns: over a 100-year period, it generates an income of approximately € 1196.000/ha. In contrast, renaturalization does not generate direct income, due to the absence of an associated economic activity.

In terms of carbon market income, afforestation provides the highest benefit, with a GHG uptake value of € 89 776/ha over 100 years. On the other hand, renaturalization, being the strategy with the highest emissions, results in the lowest carbon market income, estimated at just € 17 252/ha over the same period.

When considering Ecosystem Services (ES), renaturalization emerges as the most valuable strategy, with a cumulative estimated value of € 31.2 million/ha after 100 years. Afforestation also contributes significantly, reaching € 27.7 million/ha, underlining the importance of natural land uses. In contrast, the blueberry plantation, as the only anthropized scenario, offers significantly lower ES value, only € 6.1 million/ha after 100 years.

Taking all factors into account, including ecosystem service valuation, the rewetting (renaturalization) strategy proves to be the most profitable, with a total income of € 31.28 million/ha over 100 years, followed by afforestation at € 27.83 million/ha, and blueberry plantation at € 7.24 million/ha. These outcomes are largely driven by the high value of ecosystem services, which dominate the overall balance (Fig. 10).

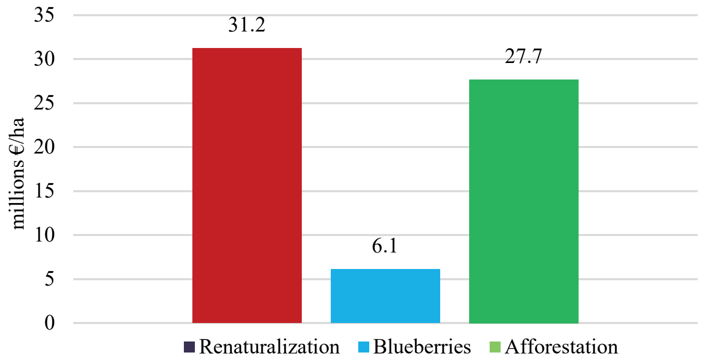

Fig. 10. Total economic evaluation comparison of the different reconversion strategies.

However, if only the "real economy" is considered, excluding ecosystem services, then the blueberry plantation scenario becomes the most profitable after-use strategy, due to the significant income derived from the sale of blueberries.

4. Conclusions and Recommendations

This study, focused on the Latvian context, aimed to evaluate alternative restoration strategies for drained peat bogs previously used for peat extraction, with the objective of identifying the most effective after-use scenario for reducing GHG emissions over a 100-year period.

Three reconversion strategies were assessed: renaturalization, blueberry cultivation, and afforestation. The latter two were also evaluated in combination with renewable energy production through the installation of solar panels and wind turbines.

The results show that all reconversion strategies reduce GHG emissions compared to leaving the bog in a drained state. Afforestation demonstrates the best performance overall, being the only scenario resulting in a net GHG uptake. Although its implementation phase produces the highest GHG emissions, the long-term benefits outweigh the initial impacts. Renewable energy systems further improve the environmental outcomes, with photovoltaic energy showing particularly favourable results. Even when only the construction-related emissions of the energy systems are considered, afforestation and blueberry cultivation still provide net GHG benefits.

The economic analysis revealed that blueberry cultivation is the most expensive to implement but offers substantial direct income through agricultural production. Afforestation provides the highest return in the carbon market due to its strong carbon sequestration performance. However, the inclusion of ecosystem services fundamentally shifts the balance. Ecosystem services deliver the highest economic value, significantly exceeding all other income sources. In this respect, renaturalization emerges as the most advantageous strategy, despite the lack of direct revenue. This highlights the critical importance of maintaining and restoring natural ecosystems, not only for climate regulation but also for the broader services they provide.

It must be noted that these results are subject to a degree of uncertainty. The long-term evolution of GHG emissions from restored peatlands is not well documented in the literature, and peatland ecosystems are highly sensitive to variables such as pH, nutrient availability, water level, and temperature [28]. These conditions, along with the unpredictable effects of climate change, can shift a system from a carbon sink to a carbon source within a short time frame. As such, this study should be considered indicative, and the selection of a reconversion strategy should always be supported by a detailed, site-specific assessment to maximize effectiveness and ensure sound investment decisions.

Further improvements to the LCA model are also possible. This study includes several limitations. The modelling framework is deterministic because uncertainty ranges and sensitivity analyses could not be produced with available data. N_2O emissions were excluded due to insufficient reliable datasets, and several scenario assumptions – including constant blueberry emissions, high fertiliser rates for afforestation, and the 25 % land-use limit for renewable energy – introduce additional uncertainty. The economic analysis is also strongly influenced by the ecosystem-service valuation methodology and discount-rate assumptions. These constraints mean that results should be interpreted primarily as comparative insights rather than precise quantitative forecasts. Adding more detailed data for the implementation phase and including management activities over time would enhance the accuracy of the results. Additionally, expanding the scope of the LCA to include economic and social indicators would allow for a more complete sustainability evaluation.

Reducing GHG emissions remains one of the most urgent challenges facing society. While no single solution can address the issue entirely, the accumulation of targeted actions across sectors can lead to significant progress. In this context, the restoration of degraded peatlands represents a valuable opportunity. With their natural capacity for carbon storage, peatlands can become either a threat if left unmanaged or a powerful ally if restored and maintained through informed, sustainable practices.

ANNEX OF TABLES

LCI INTEGRATION

Table 1A provides the information used for the rewetting scenario. The data are normalized for the FU of the study.

TABLE 1A. LCI INTEGRATION FOR THE REWETTING SCENARIO

Ecoinvent processes/materials	Amount	Unit
Inorganic phosphorus fertiliser, as P2O5 {LV}| market for inorganic phosphorus fertiliser, as P2O5 | Cut-off, U	150	kg
Grass silage, organic {GLO}| market for grass silage, organic | Cut-off, U	3000	kg
Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	2930	MJ
Excavation, hydraulic digger {RER}| excavation, hydraulic digger | Cut-off, U	116	m^3
Transport, tractor and trailer, agricultural {CH}| transport, tractor and trailer, agricultural | Cut-off, U	30	tkm

Table 2A provides the information used for the blueberry's cultivation scenario. The data are normalized for the FU of the study.

TABLE 2A. LCI INTEGRATION FOR THE BLUEBERRIES CULTIVATION SCENARIO

Ecoinvent processes/materials	Amount	Unit
Inorganic phosphorus fertiliser, as P2O5 {LV}| market for inorganic phosphorus fertiliser, as P2O5 | Cut-off, U	160	kg
Inorganic potassium fertiliser, as K2O {LV}| market for inorganic potassium fertiliser, as K2O | Cut-off, U	160	kg
Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	1380	MJ
Excavation, hydraulic digger {RER}| excavation, hydraulic digger | Cut-off, U	116	m^3
Transport, freight, light commercial vehicle {Europe without Switzerland}| transport, freight, light commercial vehicle | Cut-off, U	1.25	tkm

Table 3A provides the information used for the afforestation scenario. The data are normalized for the FU of the study.

TABLE 3A. LCI INTEGRATION FOR THE AFFORESTATION SCENARIO

Ecoinvent processes/materials	Amount	Unit
Inorganic phosphorus fertiliser, as P2O5 {LV}| market for inorganic phosphorus fertiliser, as P2O5 | Cut-off, U	10	t
Organic nitrogen fertiliser, as N {GLO}| market for organic nitrogen fertiliser, as N | Cut-off, U	4	t
Tree seedling, for planting {RER}| market for tree seedling, for planting | Cut-off, U	1000	p
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U	1200	kg
Diesel, burned in agricultural machinery {GLO}| diesel, burned in agricultural machinery | Cut-off, U	42 500	MJ
Excavation, hydraulic digger {RER}| excavation, hydraulic digger | Cut-off, U	32	m^3

Table 4A summarizes the key parameters and input data used to model the technological implementation of solar and wind energy systems integrated within the blueberry cultivation and afforestation reconversion scenarios. The data are normalized for the FU of the study.

TABLE 4A. LCI INTEGRATION FOR THE ENERGY PRODUCTION SCENARIOS

Ecoinvent processes/materials	Amount	Unit
Electricity, high voltage {LV}| electricity production, wind, 1–3MW turbine, onshore | Cut-off, U	17.9	MWh
Electricity, low voltage {DE}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U	185	MWh

ECONOMIC CONSIDERATION

Table 5A summarizes the economic activity for blueberry plantations and afforestation. They are cumulative and obtained from the JTP Groundwork tool.

TABLE 5A. ECONOMIC ACTIVITIES SUMMARIES FOR THE DIFFERENT SCENARIOS

Indicator	**Unit**	**5 years**	**10 years**	**25 years**	**50 years**
Blueberry plantation					
Revenue (Cumulative) (Average)					
Revenue	EUR/ha	3000	165 000	454 800	1 020 600
Expenses (Cumulative) (Average)					
Cost of production	EUR/ha	1500	82 500	227 400	510 300
Maintenance costs	EUR/ha	6580	14 180	36 980	74 980
Refurbishment costs	EUR/ha	–	–	5000	10 000
Total costs	EUR/ha	21580	96 680	269 380	595 280
Balance	**EUR/ha**	**8420**	**68 320**	**185 420**	**425 320**
Afforestation					
Revenue (Cumulative) (Average)					
Revenue	EUR/ha	–	–	23 954	47 908
Expenses (Cumulative) (Average)					
Cost of production	EUR/ha	–	–	9581	19 163
Maintenance costs	EUR/ha	360	360	480	840
Refurbishment costs	EUR/ha	–	–	870	1740
Total costs	EUR/ha	360	360	10 931	21 743
Balance	EUR/ha	−360	−360	13 022	26 164

Table 6A highlights the ecosystem values instead. The assessment includes the monetary valuation of ecosystem services provided by each land-use scenario, classified into provisioning, regulating, and cultural services. The values are cumulative and were derived using the JTP Groundwork tool, which quantifies the economic benefits associated with ecosystem functions such as resource provision, carbon sequestration, and recreational value.

TABLE 6A. ECOSYSTEM VALUES EVALUATION

Indicator	**Unit**	**5 years**	**25 years**	**50 years**
Blueberry plantation				
Provisional services	EUR/ha	97	97	97
Regulatory services	EUR/ha	21 645	46 433	47 993
Cultural services	EUR/ha	12.82	12.82	12.82
Total	**EUR/ha**	**21 755**	**46 543**	**48 103**
Afforestation				
Provisional services	EUR/ha	1648	1648	1648
Regulatory services	EUR/ha	173 687	195 870	205 569
Cultural services	EUR/ha	19.23	19.23	19.23
Total	**EUR/ha**	**175 354**	**197 537**	**207 236**
Renaturalization				
Provisional services	EUR/ha	20 930	40 115	40 115
Regulatory services	EUR/ha	167 394	179 883	196 440
Cultural services	EUR/ha	19.00	68.00	116.87
Total	**EUR/ha**	188343	220066	236672

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