



Baseline Setting and Carbon Credit Quantification in Improved Forest Management: A Demonstrative Case Study



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ARTICLE INFO

Keywords:

Carbon Farming
CRCF
VCM
carbon crediting
CO₂
EU climate policy

ABSTRACT

Improved Forest Management (IFM) is expected to become a key component of the EU's Carbon Removal Certification Framework (CRCF), yet baseline setting, additionality assessment, and carbon-removal quantification remain methodologically challenging. This study presents a demonstrative IFM case using a 4.7-hectare Scots pine–hornbeam stand in Western Hungary, combining extended rotation with climate-adaptive regeneration. A hypothetical baseline was derived from National Forestry Database data, while carbon sequestration was modelled using the Forest Industry Carbon Model with a 15% uncertainty correction. Project-related emissions were quantified under the IPCC guidelines. Over 2024–2055, total biomass carbon increased by 99 tC, with regeneration contributing an additional 44 tC. After deducting baseline sequestration and minor implementation emissions (<1% of total removals), the project generates 201 eligible carbon credits, equivalent to 10,074 EUR (7,255 EUR at present value). The case study illustrates how CRCF-aligned IFM assessments can be conducted in practice, stressing the importance of baseline definitions, the strong net-positive carbon balance of IFM measures, and the potential economic viability of such projects under forthcoming EU carbon removal standards.

TANULMÁNY INFÓ

Kulcsszavak:

Carbon Farming
CRCF
VCM
karbonkredit
CO₂
EU klímapolitika

KIVONAT

Baseline-meghatározás és karbonkreditszámítás klímabarát erdőgazdálkodási projektekben: egy szemléltető esettanulmány. A klímabarát erdőgazdálkodás (Improved Forest Management, IFM) várhatóan az EU Karbantartási Keretrendszerének (CRCF) egyik kulcselemévé válik, ugyanakkor a baseline meghatározása, az addicionalitás vizsgálata és a széneltávolítás számszerűsítése továbbra is módszertani kihívást jelent. Tanulmányunk egy IFM esettanulmányt mutat be egy 4,7 hektáros gyertyán elegyes erdőfenyő állomány példáján Nyugat-Magyarországon, amely a vágásforduló meghosszabbítását klímavédelmi szerkezetátalakítással kombinálja. A hipotetikus baseline-t az Országos Erdőállomány Adattár adatai alapján határoztuk meg, míg a szénmegkötést a Forest Industry Carbon Model segítségével modelleztük, 15%-os bizonytalansági korrekció alkalmazásával. A projekthez kapcsolódó emissziókat az IPCC iránymutatások szerint számszerűsítettük. A 2024–2055 közötti időszakban a biomasszában tárolt szén 99 tC-vel nőtt, míg a klímavédelmi szerkezetátalakítás további 44 tC többletet eredményezett. A baseline és a kivitelezési munkálatokból származó emissziók (a teljes szénmegkötés <1%-a) levonását követően a projektben 201 elszámolható karbonkredit keletkezik, amelynek értéke 10 074 euró (jelenértéke 7 255 euró). Az esettanulmány rávilágít a baseline-meghatározás kulcsszerepére, az IFM projektek nettó pozitív szénmérlegére és gazdasági potenciáljára.

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1 INTRODUCTION

Forests play a vital role in global and European climate strategies, serving simultaneously as carbon sinks, biodiversity reservoirs, and essential ecosystem service providers. Sustainable forest management has gained strategic importance in the context of accelerating climate change, not only for maintaining ecological integrity but also for enhancing the sector's contribution to climate mitigation (Verkerk et al., 2022; IPCC 2023). Integrating nature-based solutions into climate policy has become increasingly prominent as the European Union advances toward its 2050 climate neutrality target (Korosuo et al., 2023). One of the most significant regulatory developments in this area is the forthcoming EU Carbon Removal Certification Framework (CRCF, EU/2024/3012), which establishes harmonized rules for quantifying, verifying, and certifying carbon removals across the Union (Borovics et al., 2025). Within this emerging framework, Improved Forest Management (IFM) represents a key category of Carbon Farming activities that can generate certifiable carbon dioxide removal credits. Unlike afforestation projects, IFM interventions happen in existing forests, utilizing their already substantial biomass stocks and ecological functions. IFM encompasses a broad range of silvicultural practices—such as extended rotations, climate-adaptive stand conversion, reduced-impact harvesting, assisted natural regeneration, and deadwood retention—that may increase carbon sequestration or reduce emissions relative to a defined baseline scenario. Despite their large theoretical potential, designing, quantifying, and verifying IFM projects remains methodologically complex, with uncertainties surrounding baseline determination, additionality, long-term monitoring, and economic feasibility (McDonald et al., 2021).

The CRCF aims to provide clarity by establishing standardized, science-based procedures for estimating carbon sequestration, setting regional and forest-type-specific baselines, correcting for modelling uncertainty, and accounting for project-related emissions. However, the detailed methodological guidance for IFM projects has not yet been finalized, creating a need for demonstrative analyses that explore how such projects could be assessed once the regulatory framework is in place. Case studies can play an essential role in illustrating the practical application of the CRCF principles, identifying key parameters, and highlighting the challenges and opportunities associated with IFM-based carbon credit generation.

1.1. Rules of the CRCF regulation and types of improved forest management projects

The CRCF Regulation classifies IFM projects as forestry Carbon Farming projects. At the start of an IFM project, it is necessary to estimate the project's total future carbon sequestration, which is a component of the project initiation documentation and the Certificate of Compliance.

Regular monitoring activities (at least every five years) are also required when implementing forestry projects. Whether the planned carbon sequestration has actually been achieved on site is assessed via dendrometric measurements and soil carbon measurements. Field measurements can be complemented by remote sensing-based assessments.

Carbon-dioxide units (also referred to as credits) are issued ex post; therefore, only carbon sequestration that has already been realized can generate credits. One ton of sequestered CO₂ corresponds to one carbon credit unit. Typically, the first on-site audit occurs in the fifth year of the project, after which credit issuance can occur (*Figure 1*). However, the Compliance Certificate issued at the project start already allows the forest manager to conclude a pre-agreement with a financier who will later become the owner of the generated credits, making it possible for the forest manager to receive income even before the first monitoring ends. The expected duration of IFM projects is 30 years, with an additional 10-year monitoring period. Naturally, the option to extend the project exists, which also implies extending the monitoring period.

| Year | Events | Forest Manager | Certifier / Auditor | Project Developer | Certification System Owner |
|------|-------------------------|-------------------------------------|--|---|-------------------------------------|
| 0 | Project start | Applies for a certificate | Issues a certificate validating the eligibility of the project | Signs pre-agreement with FM Pays partial fee in advance to FM | Opens carbon account for CF project |
| 5 | First monitoring | Carries out carbon farming activity | Issues a certificate verifying the additional carbon sequestered in the first five years | Sells carbon credit on voluntary carbon market Rolling payment to FM | Registers carbon credits |
| : | : | : | : | : | : |
| 30 | Project end | Further maintains carbon pool | Issues a certificate verifying additional carbon sequestered over the last five years | Clearing fee balance with FM* | Registers carbon credits |
| 40 | Final monitoring | | Issues a certificate verifying the storage of carbon sequestered during the project period | | |

*Payments methods and schedule are unclear; one option is presented here.

Figure 1. Flowchart of the CRCF certification process

The realized carbon sequestration for IFM projects must be compared against a baseline value under the CRCF regulation. The European Commission determines the baseline value in a delegated act, in the form of a detailed methodological guidance document. Currently, IFM methodological guidance is not yet available; therefore, the baseline values are also unknown. Forest type and region determine the baseline by integrating remote sensing data, field measurements, and forest stand modelling. The present study provides an example of how such a baseline could be calculated; however, the example is theoretical and hypothetical. The actual calculation method the European Commission applies will likely differ despite similarities in underlying logic and concept.

Which IFM projects will be considered eligible is unknown. Eligibility depends on unpredictable legislative decisions. *Table 1* summarizes the most important IFM project types currently known on the voluntary carbon market. It is assumed that some will be included among the IFM project types recognized under the CRCF in the future.

1.2 Study aims

This study demonstrates how an IFM project is assessable under the emerging principles of the EU CRCF. Using a real forest stand as a case example, the study illustrates the steps required for baseline determination, quantifies the net carbon sequestration achieved through extended rotation and climate-adaptive stand conversion, estimates the resulting volume of potential carbon credits, and provides an initial indication of the project’s expected carbon-credit revenues.

2 MATERIALS AND METHODS

2.1 Description of the project site

The proposed project is an extended rotation intervention complemented by climate-adaptive stand conversion. The project site is the Káld 75/C forest subcompartment, which is a part of

the Farkaserdő forest (Figures 2 and 3). The 4.7-hectare subcompartment (Figure 4) is not part of the Natura 2000 network and is designated primarily for timber production, managed under a clear-cut silvicultural system. Its naturalness is classified as a transitional forest, with no management restrictions in place.

The upper canopy layer consists almost exclusively of Scots pine (*Pinus sylvestris*), with hornbeam (*Carpinus betulus*) forming the lower canopy. Apart from the stand edges, shrub and herb layers are largely absent. The Scots pine cohort is 99 years old, while the hornbeam cohort is 69 years old. The stand has already exceeded rotation age by nine years, and its health shows a declining trend. Field inspections confirmed that the amount of deadwood and drying trees has increased compared to the state described in the most recent forest management plan.

Table 1. Types of Improved Forest Management projects on the current voluntary carbon market, which is not yet regulated by the CRCF

| Project type | Description |
|---|---|
| Extended rotation | Delaying timber harvesting to maintain in-situ carbon storage and allow additional carbon sequestration from the atmosphere. To meet additionality criteria, this project type can only be implemented in harvest-mature stands where no legal barriers to final felling exist. |
| Climate-friendly harvesting technology | Increasing the environmental performance of harvesting operations (e.g., soil-protecting extraction), thereby reducing carbon losses from soil and biomass. |
| Omission of thinning / increased stand density | Discontinuing thinning to increase in-situ carbon stocks; may be combined with underplanting or measures supporting natural regeneration to enhance carbon sequestration. |
| Climate-adaptive stand conversion | Modifying species composition to favor native or climate-resilient species with higher carbon-sequestration potential. |
| Replacement of fast-growing species with slower-growing, long-lived species | Introducing long-lived native species that produce more durable biomass and improve the stand's naturalness. |
| Conversion to continuous-cover forestry | Ensuring continuous forest cover in areas where it was not previously required and where no legal obligation exists. Establishing mixed and uneven-aged stand structures to increase forest stability and carbon-sequestration and storage capacity. |
| Support for natural regeneration | Protecting naturally emerging regeneration, increasing the diversity of existing regeneration, and implementing additional measures that support climate adaptation. |
| Retention of deadwood | Leaving standing and laying deadwood on site in quantities exceeding legal requirements to enhance in-situ carbon storage and biodiversity. |
| Avoided salvage logging in damaged forests | Leaving trees on site after storm or fire damage to preserve carbon stocks. |



Figure 2. Photo record of the Káld 75/C forest subcompartment



Figure 3. Deadwood and stand decline observed in the Káld 75/C subcompartment



Figure 4. Location of the Káld 75/C forest subcompartment (Source: National Forestry Map <https://erdoterkep.nebih.gov.hu/>)

To determine the current and future climatic conditions of the project site, we used the SiteViewer 3.0 (Illés et al., 2024) application, an essential decision-support tool in the planning process. Based on the climate-type layer for the recent past, the tool shows that the area fell within the hornbeam–oak climate zone during the 1981–2010 period. Under present climatic conditions (Führer et al., 2011), the site is classified as sessile oak–Turkey oak climate. The program recommends the following target stand types for the current period: Scots pine (*Pinus*

sylvestris), Turkey oak (*Quercus cerris*), grey poplar (*Populus × canescens*), and black locust (*Robinia pseudoacacia*). Scots pine dominates the existing stand on the site. The area is projected to remain within the sessile oak–Turkey oak climate zone in the near future (2041–2070), and the recommended target stand types for this period also remain Scots pine, Turkey oak, grey poplar, and black locust. Neither the climate classification nor the recommended target stand types change for the more distant future (2071–2100).

Table 2 summarizes the site conditions and the current and projected climatic characteristics of the project area. The site characteristics were also verified through on-site inspection during the planning process.

Table 2. Site-type characteristics and extent of the examined forest subcompartment.

| Site | Area (ha) | Climate 2011–2040 | Climate 2041–2070 | Hydrology | Genetic soil type | Soil depth | Soil texture |
|-----------|-----------|----------------------|--------------------------------|------------------------------|-------------------|------------|--------------|
| Káld 75/C | 4.7 | Hornbeam–oak climate | Sessile oak–Turkey oak climate | Not affected by excess water | Rusty forest soil | Deep | Sand |

2.2 Description of the Proposed Project

An extended rotation project complemented by climate-adaptive stand conversion is the proposed intervention. The planned project duration is 30 years; therefore, all projections extend to the 2055 target year.

The purpose of the extended rotation is to maintain the stand beyond its typical rotation age, to prolong in-situ carbon storage, and achieve additional carbon sequestration. The resulting carbon sequestration is considered additional because the stand would have been harvested under a Business as Usual (BAU) scenario.

Given the substantial amount of dieback within the stand, we also plan to implement gap-based regeneration on a total area of 0.47 hectares, after removing dead trees. Regeneration will be with drought-tolerant species better adapted to the climatic conditions expected at the site. As such, this intervention also qualifies as climate-adaptive stand conversion. Table 3 presents the species selected for planting. The carbon sequestration achieved through this climate-adaptive structural transformation is also considered additional, since the existing forest management plan does not prescribe such a conversion; therefore, intervention is motivated directly by the incentives of the voluntary carbon market and is implemented specifically in connection with the planned Carbon Farming project.

Table 3. Tree species planned for planting and the corresponding regenerated area.

| Tree species | Share of regenerated area (%) | Area (ha) |
|--|-------------------------------|-----------|
| Turkey oak (<i>Quercus cerris</i>) | 40% | 0.188 ha |
| Field maple (<i>Acer campestre</i>) | 10% | 0.047 ha |
| Field elm (<i>Ulmus minor</i>) | 10% | 0.047 ha |
| Aspen (<i>Populus tremula</i>) | 20% | 0.094 ha |
| Silver linden (<i>Tilia tomentosa</i>) | 20% | 0.094 ha |

2.3 Establishing the baseline

Baseline determination in IFM projects is uncertain. According to the CRCF Regulation, the baseline will be established by the European Commission in a standardized manner for each forest type and region, based on the integration of remote-sensing information, field measurements, and forest-stand modelling. The baseline represents the average level of carbon sequestration that can reasonably be expected from a given forest stand under normal management conditions without any additional intervention. The detailed rules for IFM projects—including the baseline values—will be delineated in a methodological guidance document that the Commission publishes as a delegated act. As this guidance has not yet been released, the future baseline values remain unknown.

This article provides a hypothetical example of baseline determination. For this purpose, we use data from the National Forestry Database and consider Scots pine stands aged 101–120 years. We assume that the baseline corresponds to the average annual increment expressed in CO₂ equivalent for stands within this age range. *Table 4* presents the resulting baseline value calculated in this manner.

We applied the age-class average increment from the National Forestry Database as a transparent and empirically grounded proxy for the CRCF-type baseline. Importantly, under the CRCF logic, the baseline is defined in terms of carbon flow (annual net sequestration) rather than standing carbon stock; therefore, an age-class average increment expressed in CO₂ equivalent directly corresponds to the regulatory concept of a flow-based reference level. In constructing this proxy baseline, we performed explicit stratification by tree species (Scots pine) and age class (101–120 years), thereby reflecting both forest-type specificity and structural development stage. This stratified approach mirrors the CRCF principle that baselines should be differentiated by forest type and regional characteristics rather than applied uniformly across heterogeneous stands. The selected age class represents biologically and legally harvestable stands and thus approximates the business-as-usual counterfactual in an even-aged rotation system. Because the National Forestry Database relies on standardized national inventory methods and large sample sizes, the resulting increment value reflects empirically observed management conditions. While the final CRCF methodology may introduce additional stratification variables, the adopted approach provides a conceptually aligned, flow-based, and structurally differentiated approximation of a standardized CRCF baseline.

The resulting baseline value indicates a relatively small carbon sink (expressed with a negative sign, in line with IPCC greenhouse gas accounting conventions where CO₂ removals are reported as negative emissions). This modest annual sequestration rate is consistent with the biological characteristics of older stands in the 101–120-year age class, where growth typically slows compared to earlier developmental stages. Consequently, the baseline reflects a realistic and low yet still positive net carbon uptake under business-as-usual management conditions for mature Scots pine stands.

Table 4. Baseline value for Scots pine stands aged 101–120 years (negative values indicate net CO₂ sequestration in line with IPCC conventions).

| Baseline unit | Baseline value |
|--|----------------|
| m ³ net annual increment/ha/year | 0.74 |
| m ³ net annual increment /year (for 4.7 ha) | 3.48 |
| tCO ₂ /ha/year | –0.72 |
| tCO ₂ /year (for 4.7 ha) | –3.4 |

2.4 Methodology for quantifying emissions associated with harvesting, planting, and tending operations

The operations listed in *Table 5* will be performed during the planned gap-based regeneration activities. In accordance with the methodological requirements of the CRCF Regulation, we calculated the carbon dioxide, nitrous oxide (N₂O), and methane (CH₄) emissions associated with these operations. Fuel consumption related to regeneration activities was estimated following the guidelines of Erdeiné Késmárki-Gally and Rák (2020), using an approach similar to that applied by Benke et al. (2015) and Borovics et al. (2025). Emissions related to timber harvesting were quantified based on the methodology of Polgár et al. (2018). We applied the most recent conversion factors provided by the IPCC for agricultural and forestry machinery (IPCC 2006, 2019) to estimate greenhouse gas emissions from the combustion of diesel and gasoline. Fuel-consumption coefficients and emission factors are subject to parameter uncertainty, reflecting variability in machine type, engine efficiency, operational load, maintenance status, and site conditions. The applied fuel-use values are based on published national averages, and the emission factors follow IPCC default parameters commonly used in national greenhouse gas inventories.

Table 5. Planned harvesting, regeneration, and tending operations during the implementation of the IFM project, and the land-category classification of the project.

| Year | Operation | Machine type | Frequency | Fuel consumption (liter) |
|-------------------|--|--|--------------------------|--------------------------|
| Land category: I. | | | | |
| | Removal of Scots pine and hornbeam deadwood in designated gaps | Tractor-pulled forestry trailer with crane | 1× (210 m ³) | 240.9 |
| Year 1 | Manual mowing and hand scything | – | 1× | – |
| | Planting with planting spade | – | 1× | – |
| | Row clearing | Brush cutter | 4× | 112.8 |
| Year 2 | Row clearing | Brush cutter | 4× | 112.8 |
| | Replanting | Planting bar | 1× | 55 |
| Year 3 | Row clearing | Brush cutter | 4× | 112.8 |
| | Replanting | Planting bar | 1× | 55 |
| Year 4 | Row clearing | Brush cutter | 4× | 112.8 |
| Year 5 | Row clearing | Brush cutter | 4× | 112.8 |
| Year 6 | Row clearing | Brush cutter | 4× | 112.8 |
| Year 7 | Row clearing | Brush cutter | 4× | 112.8 |

2.5 Calculation of carbon sequestration and carbon credit revenues

Carbon sequestration in the forest stand included in the IFM project was quantified using the Forest Industry Carbon Model (Borovics et al., 2024), which allows for the projection of carbon stocks in forest biomass, soil, dead organic matter, harvested wood products, and product-substitution effects. Using the model, we calculated carbon dioxide sequestration in aboveground and belowground biomass. We assumed equilibrium over the project period for soil, deadwood, and litter carbon pools. This conservative assumption is consistent with the provisions of the CRCF Regulation.

The projection was conducted for 2024–2055. The site productivity (yield class) of the selected tree species was determined using the SiteViewer 3.0 application, based on climatic data for the 2041–2070 period. Yield tables were assigned to each tree species according to the

same matching rules as those applied in the National Forestry Database.

The amount of eligible carbon sequestration is the quantity that forms the basis for credit issuance on the voluntary carbon market. According to the CRCF Regulation and the draft methodological guidelines, this quantity is obtained by correcting the modelled forest carbon sequestration with a factor that reflects modelling uncertainty, and then subtracting fossil fuel-based greenhouse gas emissions associated with harvesting, planting, and tending operations, as expressed in Equations (1)–(4):

$$(1) \text{ Eligible carbon sequestration} = (CR_{\text{baseline}} - CR_{\text{total}}) \times (1 - UNC) - GHG_{\text{associated}} > 0$$

$$(2) CR_{\text{baseline}} = -3,4 \frac{tCO_2}{\text{year}}$$

$$(3) CR_{\text{total}} = CR_{\text{biomass}} + CR_{\text{soil}}$$

$$(4) GHG_{\text{associated}} = GHG_{\text{fossil fuel}} + GHG_{\text{fertilizer}}$$

Where:

CR_{baseline} : is the baseline value, i.e., the assumed reference level of carbon sequestration;

CR_{total} : is the total carbon sequestration of the IFM project;

$GHG_{\text{associated}}$: denotes the additional GHG emissions associated with harvesting, regeneration, and tending operations;

CR_{biomass} : is carbon sequestration in biomass;

CR_{soil} : is carbon sequestration in soil, which in this case is assumed to be zero;

$GHG_{\text{fossil fuel}}$: represents GHG emissions from machinery used for harvesting, planting, and tending;

$GHG_{\text{fertilizer}}$: represents GHG emissions from fertilization (not relevant in this study);

UNC : is the uncertainty correction factor reflecting modelling uncertainty, set to $UNC=0.15$ in our case.

We applied an uncertainty correction factor (UNC) of 15% as a conservative expert judgement to reflect the combined modelling uncertainty associated with long-term (2024–2055) stand-level projections, mixed-species regeneration, and growth variability under changing climatic conditions. For the same Forest Industry Carbon Model, Borovics et al. (2025) report a substantially lower uncertainty deduction of approximately 3%, calculated using a statistical approach based on the relative standard deviation of modelled carbon stock changes, with uncertainty parameters derived from the Hungarian National Greenhouse Gas Inventory documentation and evaluated at a one-sided 70% confidence level. That lower value reflects uncertainties primarily associated with yield table-based modelling and field measurements under more controlled assumptions. However, in the present case study, the longer time horizon, inclusion of climate-adaptive stand conversion, and the still-unfinalized CRCF methodological rules justify applying a more precautionary deduction. To ensure transparency, we additionally provide a simple sensitivity analysis that presents carbon credits and associated revenues under alternative uncertainty factors ranging from 3% to 30%.

The eligible carbon sequestration, expressed in tons of CO₂ equivalent, determines the

number of carbon credits that can be generated. Carbon credit revenues were calculated using a carbon price of 50 EUR per tCO₂, which reflects the current price level observed for land-based voluntary carbon market (VCM) projects in Hungary, as reported by Borovics et al. (2024). The value is consistent with recent European transactions for nature-based carbon removal credits and represents a realistic market-based assumption rather than a speculative forward projection. At the same time, within the context of the emerging EU carbon removal certification system and potential credit purchasing programs, the European Commission has signalled that higher price levels may materialize in the medium term, with figures around or above 100 EUR per tCO₂. The present revenue values were derived using a real discount rate of 2%, reflecting a moderate social discount rate commonly applied in long-term climate and land-use policy assessments within the EU context.

3 RESULTS

Figure 5 shows the development of carbon stocks in the living biomass of the forest stand included in the IFM project for the projection period up to 2055. The total carbon stored in biomass increases from 527 tons to 671 tons over this time, corresponding to an overall gain of 99 tons of carbon by the end of the project. Carbon stock values are reported in tons of carbon (tC), representing the absolute quantity of carbon stored in living biomass at a given point in time. By contrast, carbon sequestration (sink) values are expressed in tons of CO₂ equivalent (tCO₂) and are reported with a negative sign, in line with IPCC greenhouse gas accounting conventions, where removals from the atmosphere are recorded as negative emissions, while increases in carbon stocks are presented as positive stock changes.

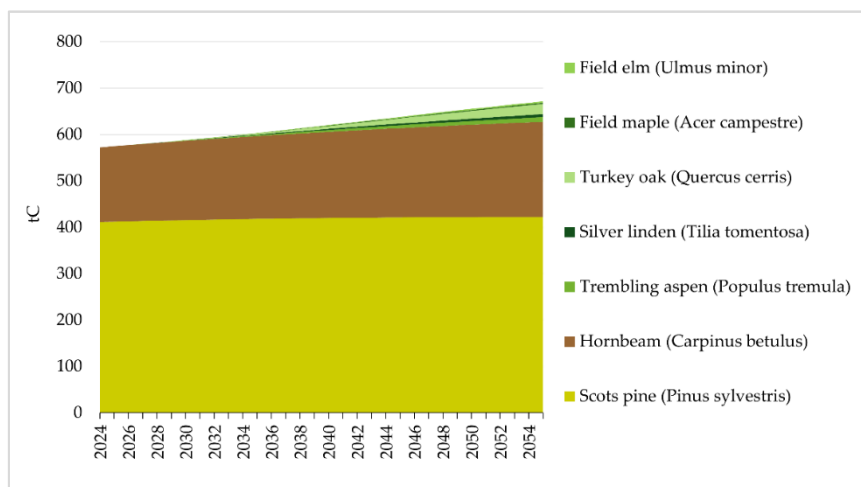


Figure 5. Development of carbon stock in the living biomass of the forest stand included in the IFM project, disaggregated by tree species, 2024–2055. (Note: Carbon stocks are reported in tons of carbon (tC) as positive stock values, in accordance with IPCC greenhouse gas reporting conventions.)

Figures 6 and 7 separately illustrate the evolution of carbon stocks and annual carbon sequestration for the tree species introduced through gap-based regeneration.

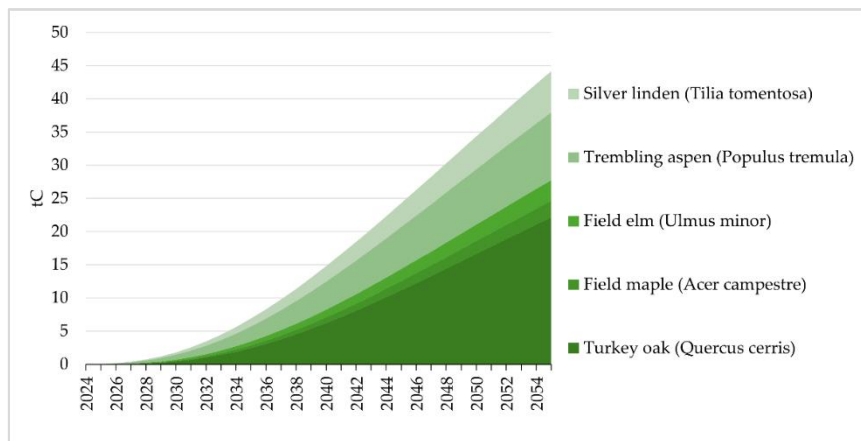


Figure 6. Development of carbon stocks of the tree species introduced through group-regeneration, 2024–2055. (Note: Carbon stocks are reported in tons of carbon (tC) as positive stock values, in accordance with IPCC greenhouse gas reporting conventions.)

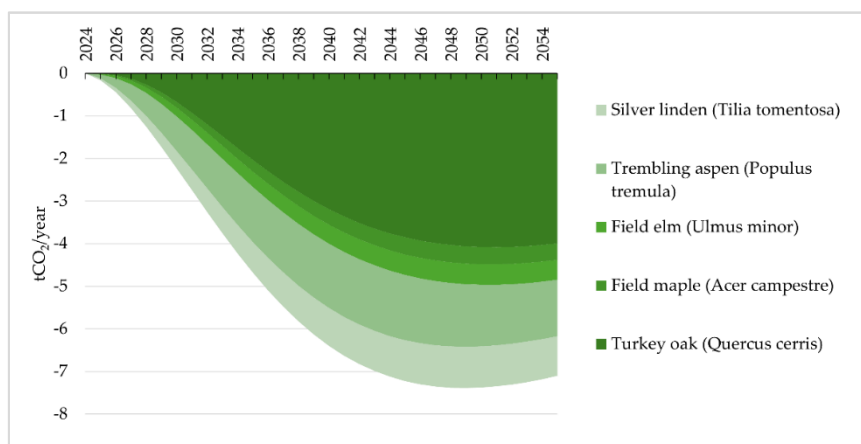


Figure 7. Development of carbon sequestration of the tree species introduced through group-regeneration, 2024–2055. (Note: Carbon sequestration is expressed in tons of CO₂ equivalent (tCO₂) and reported with a negative sign, in accordance with IPCC greenhouse gas accounting conventions, where removals from the atmosphere are recorded as negative emissions.)

Gap-based regeneration contributes a total of 44 tons of additional sequestered carbon by the end of the project period. The average annual carbon dioxide sequestration within the regenerated gaps amounts to -5.1 tCO₂ per year.

Figure 8 shows the annual total carbon sequestration alongside the greenhouse gas (GHG) emissions associated with harvesting, regeneration, and tending operations, expressed in CO₂ equivalents. The figure also displays the uncertainty correction factor applied to account for modelling uncertainty, which reduces the amount of carbon eligible for crediting. For clarity, total forest carbon sequestration is divided into the portion eligible for carbon crediting and the portion used to offset project-related emissions. According to our calculations, GHG emissions from machinery amount to 0.7% of the total carbon sequestered by 2055.

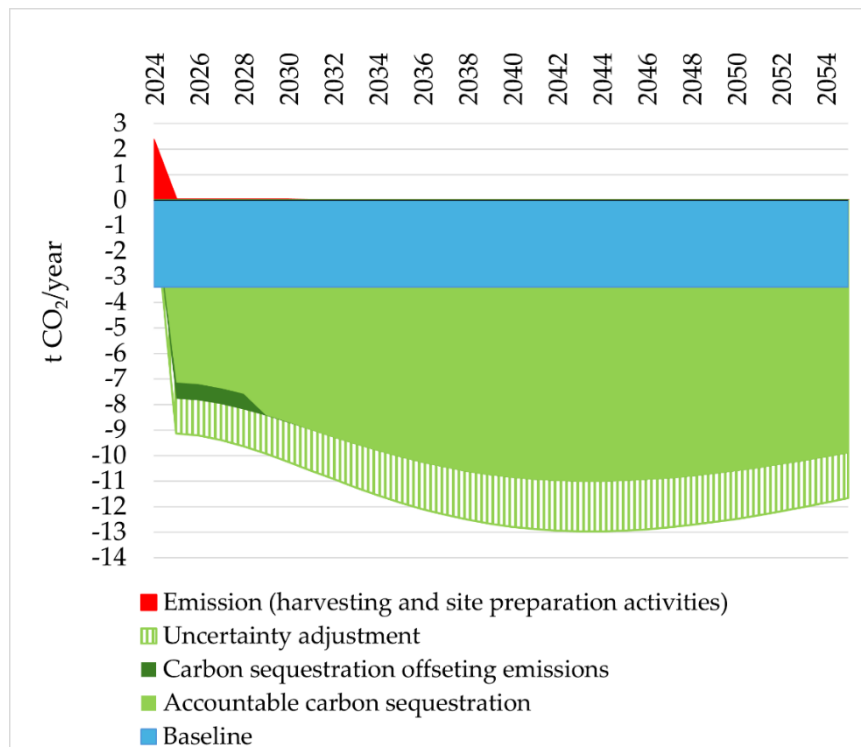


Figure 8. Eligible carbon sequestration in the IFM project, GHG emissions associated with harvesting, regeneration and tending activities, the carbon amount offsetting these emissions, and the uncertainty correction factor, 2024–2055. (Note: Carbon sequestration is expressed in tons of CO₂ equivalent (tCO₂) and reported with a negative sign in accordance with IPCC greenhouse gas accounting conventions, where removals from the atmosphere are recorded as negative emissions.)

The total revenue from carbon credits generated by the IFM project over the 2024–2055 period is estimated at 10,074 EUR, with a present value of 7,255 EUR (Figure 9).

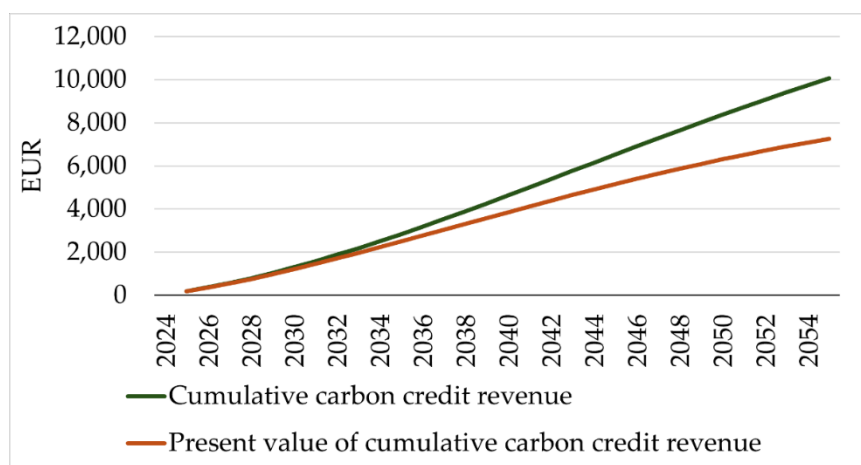


Figure 9. Cumulative carbon-credit revenue and its present value for the IFM project over the 2024–2055 period, for the 4.7-hectare project area.

Table 6 summarizes total carbon sequestration, associated GHG emissions, the resulting number of carbon credits, and the projected carbon-credit revenue. When expressed per hectare, the carbon-credit revenue equals 2,132 EUR/ha over the full duration of the project.

Table 6. Carbon sequestration, GHG emissions from harvesting, regeneration and tending operations, and the resulting carbon credits and carbon-credit revenue for the IFM project.

| Site | Area (ha) | Carbon sequestration (tCO ₂) | CO ₂ emissions (kg) | N ₂ O emissions (kg) | CH ₄ emissions (kg) | Credits (units) | Credits per ha (units/ha) | Revenue (EUR) | Revenue per ha (EUR/ha) |
|-----------|-----------|--|--------------------------------|---------------------------------|--------------------------------|-----------------|---------------------------|---------------|-------------------------|
| Káld 75/C | 4.7 | -364 | 2,524.6 | 0.01 | 0.2 | 201 | 43 | 10,074 | 2,132 |

Figure 10 displays the present value of total carbon credit revenues at varying carbon price levels. Carbon prices are expected to increase with the entry into force of the CRCF Regulation and the launch of the regulated voluntary market. Figure 10 shows how such changes in carbon prices would influence the project's revenue (expressed in present value).

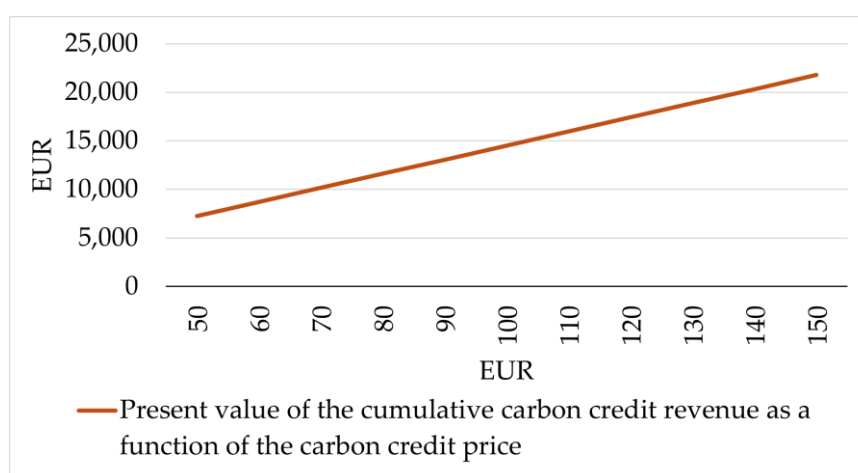


Figure 10. Present value of cumulative carbon-credit revenue under different carbon price levels for the 4.7-hectare IFM project area.

Figure 11 demonstrates that the number of eligible carbon credits and the corresponding present value of carbon credit revenues decline almost linearly as the uncertainty correction factor (UNC) increases from 3% to 30%. At the lower end of the range (3%), which corresponds to the statistically derived uncertainty level reported by Borovics et al. (2025) for the same model under more controlled assumptions, the project generates the highest number of credits and the highest present value. Applying the more precautionary 15% UNC used in this study results in a moderate reduction in both indicators; however, the project remains clearly revenue positive. The project still generates a substantial number of credits and a meaningful level of carbon credit revenue even under highly conservative assumptions (e.g., 25–30% UNC).

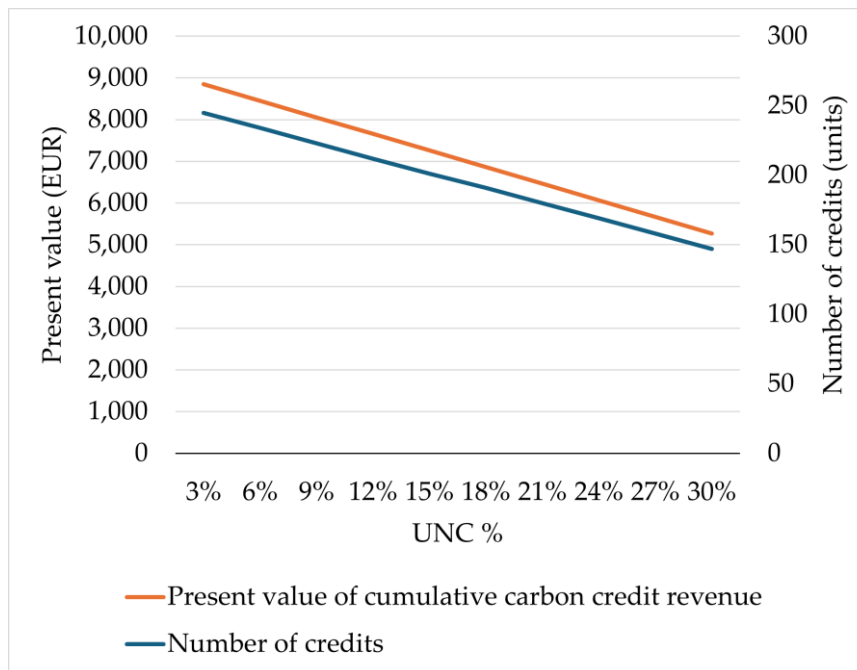


Figure 11. Sensitivity of the number of eligible carbon credits and the present value of carbon credit revenue to alternative uncertainty correction (UNC) factors (3–30%) for the 4.7-ha IFM project area.

4 DISCUSSION AND CONCLUSIONS

Improved Forest Management projects aim to optimize the carbon sequestration potential of existing forests and are expected—through the CRCF Regulation—to become an integral component of the EU’s carbon removal policy framework. Based on the findings of our case study, several key conclusions can be drawn:

(1) **Additionality and timing:** IFM projects can only be certified, and carbon sequestration can only be credited, if the implemented measures demonstrably exceed “business-as-usual” (BAU) practices and provide genuine additional carbon removals. This framework enables the inclusion of mature stands that are technically harvestable but not yet harvested. However, Scots pine stands aged 101–120 years represent an advanced developmental stage and may exhibit increasing vulnerability to climatic stress, drought events, pest outbreaks, and pathogen infections under projected future climate conditions. Although such stands may currently function as net carbon sinks, declining vitality or disturbance events could reduce growth rates or even shift the carbon balance toward net emissions. The extended-rotation approach, therefore, requires adaptive management and continuous monitoring to maintain carbon permanence.

(2) **Need for long-term commitment:** A typical project duration of 30 years, combined with an additional 10-year monitoring period, requires a substantial long-term commitment from forest owners. While essential for successful implementation, this extended period may also present challenges for landowners. Over such time horizons, disturbance risks—including windthrow, fire, bark beetle infestations, and drought-induced mortality—must be explicitly considered. Under the projected sessile oak–Turkey oak climate zone, Scots pine may face increasing physiological stress, whereas the introduced species mix (e.g., Turkey oak, field maple, field elm, aspen, and silver linden) is expected to demonstrate higher resilience to heat and water limitation. Nevertheless, no species composition is entirely risk-free under

accelerating climate change. Future CRCF methodological guidance may address such risks through buffer mechanisms, pooled risk reserves, permanence-related discount factors, or other risk-adjustment instruments similar to those applied in existing voluntary carbon market standards.

(3) The critical importance of baseline determination: Project outcomes—especially the quantity of creditable carbon removals—depend heavily on the baseline, which remains uncertain pending the adoption of the delegated act. Future methodological clarification of baseline values will strongly influence both the number of credits generated and overall project viability. In the present study, the applied baseline is explicitly hypothetical and demonstrative in nature, constructed through stratification by tree species and age class and aligned with the CRCF's flow-based accounting logic. Once the official IFM methodological guidance is adopted, additional stratification variables—such as productivity class, climatic zone differentiation, management intensity, or disturbance-risk adjustments—may be introduced, potentially requiring recalibration of baseline values and corresponding credit volumes.

(4) Economic viability and pre-financing opportunities: Our analysis indicates that IFM projects can achieve positive financial outcomes, particularly if carbon prices rise over the coming decade. The issuance of a Compliance Certificate at project initiation allows pre-financing arrangements, providing forest owners with access to funds even before the first verification audit.

(5) Carbon footprint and emissions: Project-related emissions from fossil-fuel use during harvesting, regeneration, and tending represent less than 1% of the total carbon sequestered. With appropriate planning, this confirms that IFM projects can be implemented with a strongly net-positive carbon balance.

(6) Environmental, conservation, and climate policy relevance: IFM projects simultaneously contribute to climate mitigation, biodiversity conservation, environmental protection, and sustainable forest management. Climate-adaptive stand restructuring fosters forest types better suited to future climatic conditions, thereby increasing ecosystem resilience.

(7) Role of decision-support tools: Decision-support systems such as SiteViewer 3.0 and the Forest Industry Carbon Model played a crucial role in planning and scenario development. Such digital tools are indispensable for designing scientifically robust Carbon Farming projects.

(8) Relative magnitude of carbon revenues: When interpreted in a regional economic context, the projected carbon credit revenue—approximately 71 EUR/ha/year—represents a non-negligible supplementary income stream relative to typical forest management margins in Hungary. The stumpage value of this stand's annual increment, excluding overhead and regeneration costs, is roughly 145 EUR/ha/year. Since carbon revenues do not require harvesting operations—which involve organizational tasks and management effort—and because they do not replace timber harvesting, only postpone it, this income source can be considered financially viable, depending on the landowner's individual financial objectives and preferences.

(9) Robustness of machinery-related emission estimates: Although project-related emissions from harvesting, regeneration, and tending operations account for only 0.7% of total carbon sequestration, parameter uncertainty in fuel consumption coefficients and emission factors should be acknowledged. These parameters vary depending on machine type, engine efficiency, operational load, and site conditions, and IPCC default emission factors inherently include uncertainty. However, given the relatively small absolute magnitude of machinery-related emissions compared with projected stand-level carbon sequestration, even moderate deviations in fuel consumption or emission coefficients would not materially affect the overall net carbon balance of the project. Comparable relative magnitudes of machinery-related emissions—substantially lower than total forest carbon sequestration—have also been reported by Benke et al. (2015) and Borovics et al. (2025) using similar calculation approaches, which

further supports the robustness of the present findings.

(10) Limitations and transferability: This study represents a site-specific, demonstrative case study under particular ecological, silvicultural, and regulatory assumptions. Quantitative outcomes—including baseline value, additional sequestration potential, credit volumes, and economic performance—are, therefore, context dependent and influenced by forest type, productivity class, climatic zone, rotation system, and management regime. Applying this approach to other forest types or regions would require recalibrating baseline assumptions, productivity parameters, and disturbance-risk considerations. In addition, exact numerical replication of the modelling results depends on access to the Forest Industry Carbon Model and the SiteViewer decision-support tool, as well as the yield tables and parameter settings applied. While the methodological logic is transferable, the specific quantitative outputs should be interpreted as illustrative.

Overall, IFM projects represent one of the most complex yet promising segments of the voluntary carbon market as they allow for the inclusion of far larger areas than afforestation projects alone. However, their long-term climate effectiveness depends on a robust baseline definition, adaptive risk management, and the incorporation of disturbance-related safeguards within the CRCF framework. Once the regulatory framework is finalized, their adoption is expected to increase—particularly in regions where the condition and climate sensitivity of existing forests justify such interventions.

Acknowledgments: This article was made in the frame of the project TKP2021-NKTA-43, which has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

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